DOCUMENT RESUME

ED 369 655 SE 054 391

AUTHOR Allen, Robert D.; Stroup, David J.
TITLE Teaching Critical Thinking Skills in Biology.
INSTITUTION National Association of Biology Teachers, Reston, VA.
REPORT NO ISBN-0-941212-13-0
PUB DATE 93
NOTE 59p.
AVAILABLE FROM National Association of Biology Teachers (NABT), 11250 Roger Bacon Drive, #19, Reston, VA 22090 ($15 for members, $20 for non-members, plus shipping and handling; quantity discounts available).
PUB TYPE Guides - Classroom Use - Teaching Guides (For Teacher) (052)

EDRS PRICE MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS *Biological Sciences; *Critical Thinking; *Educational Strategies; Science Activities; Science Curriculum; *Science Instruction; Science Process Skills; Scientific Concepts; Secondary Education; Secondary School Science; Teaching Methods; *Thinking Skills

ABSTRACT

Currently, the biological sciences' arsenal of information and knowledge is increasing at such a rate that teachers cannot expect or be expected to teach all the "facts" that are known. Instead many are suggesting that teachers should help students to develop an ability to use and apply fundamental concepts in a critical and analytical way. To help teachers fulfill this goal, this document provides a discussion of why critical thinking should be taught, instructional strategies, and discussions of what is effective practices, how to implement critical thinking, what difficulties students and instructors may face, and what thinking skills are emphasized on standardized tests. Contains 20 references. (ZWH)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED 369 655

aching
itica
hinking
in

SE054391

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

☒ This document has been reproduced as received from the person or organization originating it.

☐ Minor changes have been made to improve reproduction quality.

• Points of view or opinions stated in this document do not necessarily represent official OERI position or policy

"PERMISSION TO REPRODUCE THIS MATERIAL IN **OTHER THAN PAPER COPY** HAS BEEN GRANTED BY

Patricia J. McWethy

TO THE EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)."

Teaching Critical Thinking Skills in Biology

by Robert D. Allen & David J. Stroup

Published by the National Association of Biology Teachers (NABT), 11250 Roger Bacon Drive #19, Reston, Virginia 22090-5202, USA

ISBN 0-941212-13-0

Copyright © 1993 by the National Association of Biology Teachers

All rights reserved. Material from this book may be reproduced for classroom use only. This book may not be reproduced in its entirety by any mechanical, photographic or electronic process or in the form of a photographic recording, nor may it be stored in a retrieval system, transmitted or otherwise copied for any other use without written permission of the publisher.

Cover Credits: Photograph by Robert Gaines, Jr., Victor Valley Community College, Victorville, CA.

Printed by Lancaster Press, Inc., Lancaster, Pennsylvania.

ACKNOWLEDGMENTS

We wish to express our sincere appreciation to Ms. Ruby Wikstrom and Ms. Angie Cantey for their assistance in preparing the manuscript, to our students for their patience as we struggled with teaching critical thinking, and to our families for their continued encouragement and support during this project.

Table of Contents

Introduction....4

CHAPTER 1 - Why Critical Thinking?....5

CHAPTER 2 - Instructional Strategies....11

CHAPTER 3 - What Is Effective Practice?....18

CHAPTER 4 -Getting Started....32

CHAPTER 5 - Thinking Skills - What Do Standardized Tests Emphasize?....41

CHAPTER 6 - Student & Instructor Difficulties....50

Annotated Bibliography....56

Introduction

With the explosion of information and knowledge in the biological sciences, it has become obvious that we cannot hope to teach all the "facts" of biology. Our efforts will be much more productive if we focus on major, fundamental concepts and on developing students' ability to use and apply these concepts in a critical and analytical way.

As a consequence, "Critical Thinking" has become a topic of intense interest among biology teachers. There is every indication that this interest will continue to grow and will be a major influence on curriculum development and teaching. Unfortunately, teachers have had little guidance or assistance on what constitutes critical thinking, how to deal with student difficulties and how to teach critical thinking skills.

The purpose of this monograph is to assist teachers' efforts to develop the critical thinking skills of their students. Emphasis is placed on specific activities that are effective in developing thinking skills. Numerous examples are provided of strategies, techniques and exercises in a variety of biology topic areas.

Our efforts to improve critical thinking skills began more than 20 years ago. Since then, we and other teachers have developed and evaluated numerous instructional strategies and exercises that have proven effective. These are presented in this monograph as techniques and instructional materials that will be a definite aid to you and your students. It was not our intent to write a textbook or to cover every topic area in biology. Neither do we pretend to discuss all the possible teaching strategies and thinking skill exercises. Instead, this monograph presents guidelines, examples and procedures that will help you in your efforts.

"Why critical thinking?" is discussed in Chapter 1, including a brief background on research and common misconceptions about thinking skill instruction.

Chapters 2, 3 and 4 describe a variety of instructional strategies and practice exercises. These are intended to provide numerous specific examples that demonstrate the teaching of critical thinking.

Chapter 5 on standardized tests describes and illustrates how these tests require the application of critical thinking skills. We consider this chapter an important one since teachers and students must recognize first how thinking skills can be evaluated in a context outside the biology classroom and second, the specific skills being evaluated.

Application of the principles and strategies, and consistent utilization of the practice exercises described in this monograph will result in significant improvement of your students' thinking skills. This effort will not be easy and is challenging for both teachers and students. With perseverance, appropriate teaching techniques and effective instructional materials, however, this effort can be successful.

Chapter One

Why Critical Thinking?

Within the past few years much has been written about critical thinking in a variety of disciplines. There is significant movement away from the mindset that learning biology is the accumulation of a set of "facts" to be memorized. It is becoming increasingly apparent that teachers want their students to be able to do much more than just remember and recall information, and would like these students to apply concepts and information from the discipline of biology in a productive, intelligent and meaningful way. Moreover, as the information content in biology increases at a more and more rapid rate, it is becoming obvious that we cannot expect to "cover all the material." We must develop the students' skills to apply the most important content and to learn and use new information as it becomes available to solve new problems.

Reviews of critical thinking efforts and research have shown that this is not a simple or easy endeavor. Stephen Norris (1985) has extensively surveyed the literature and has identified several highlights from research on critical thinking that include the following:

Highlights from Research on Critical Thinking

• ***Critical thinking is a complex of many considerations.***
It requires individuals to assess their own and others' views, to seek alternatives, to make inferences, and to have the disposition to think critically.

• ***Critical thinking is an education ideal.***
It is not an educational option. Students have a moral right to be taught how to think critically.

• ***Critical thinking ability is not widespread.***
Most students do not score well on tests that measure ability to recognize assumptions, evaluate arguments and appraise inferences. Adults, as well, frequently make simple judgmental errors on simple problems.

• ***Critical thinking is sensitive to context.***
Students' background knowledge and assumptions can strongly affect their ability to make correct inferences. Inferences are more likely to be correct when the context relates to the individual's personal experience and when performance is not associated with threats or promises.

• ***Teachers should look for the reasoning behind students' conclusions.***
Coming up with a correct answer may not be the result of critical thinking. Essay tests are more likely to reveal the student's thought processes than are objective tests. And the tests themselves must be evaluated critically to make sure they require critical thinking skills.

• ***Simple errors may signal errors in thinking at a deeper level.***
In trying to solve complex problems, for example, students may err not just by making a miscalculation, but by using an incorrect approach to the problem. They should be encouraged to take time before solving a problem to decide how to go about finding the solution.

• ***Having a critical spirit is as important as thinking critically.***
The critical spirit requires one to think critically about all aspects of life, to think critically about one's own thinking and to act on the basis of what one has considered when using critical thinking skills.

• ***To think critically one must have knowledge.***
Critical thinking cannot occur in a vacuum; it requires individuals to apply what they know about the subject matter as well as their common sense and experience.

Norris' survey indicates the complexity of critical thinking. Clearly, this a mental, intellectual endeavor that extends well beyond accurate recall, correctness of information or clear explanation.

Despite these complexities, there is growing interest and concern for critical thinking. This is clearly demonstrated by strong recommendations from national professional organizations. In a recent National Science Foundation (1989) workshop on biology education, the participants recommended to:

Develop methods of teaching that allow for student explanation, argumentation and critical thinking, yet enable the orderly introduction of biological concepts.

and that:

New approaches to the teaching of biology at all levels must emphasize the conceptual framework of biology, reduce the excessive terminology that characterizes so many courses, and consider the strengths and limitations of the scientific process.

In another report, the National Advisory Group of Sigma Xi (1989) recommended the following:

The National Advisory Group was adamant that entry-level courses (in the sciences) should focus upon thinking, analysis, synthesis, critical reasoning and understanding and that the current emphasis on memorization of facts be minimized and, whenever possible, eliminated.

Most recently, the American Association for the Advancement of Science makes similar recommendations in *Benchmarks for Science Literacy* (1993). Strong emphasis is placed on the process of science and understanding how conclusions are drawn and interpretations are made. The goal is to enable individuals to make judgments about claims--"claims about products, about how nature of social systems or devices work, about their health and welfare, about what happened in the past or what will occur in the future...." Testing hypotheses, evaluating evidence and applying logic are key elements in the guidelines. The *Benchmarks* are intended as models and guides for curriculum development and, as such, should be a primary influence on the future direction of science teaching.

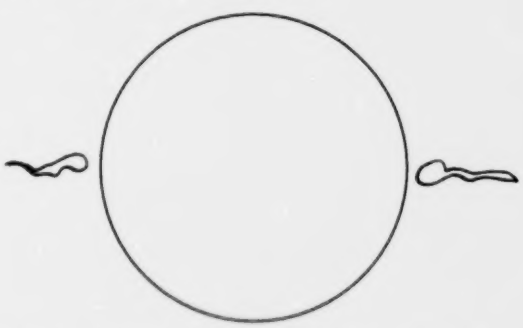
These are strongly worded and insistent positions that repeatedly emphasize the need to give much more attention to critical thinking and analytical skills. The recommendations in this monograph are equally strong and we feel that the time is right to make much needed instructional revisions. Indeed, if biology teachers respond to these recommendations, then there will be fundamental and important curriculum changes.

As impressive as these recommendations are from prestigious professional associations, they give no indication of how these goals are to be achieved. **The primary purpose of this monograph is to give teachers practical techniques and procedures that can be applied to help students achieve significant improvement in thinking skills.**

What Do We Want Our Students To Do?

You may be like many frustrated teachers who have said, "Why can't my students answer these questions? They have had all the necessary information and concepts, but if they have to do more than recall memorized answers, they are at a complete loss!" Experiences such as this provided the impetus for our first efforts to specifically develop thinking skill instruction. One instance, in particular, stands out as an exceptionally revealing example. The following question was included on a biology examination after students had covered fertilization and development in lecture:

Exam Question: Suppose two sperm attempted to enter an unfertilized frog egg at exactly opposite points on the egg at exactly the same time as shown below:



Which of the following would most likely be observed?
1. Only the one on the left would enter the egg.
2. Only the one on the right would enter the egg.
3. Both would enter the egg.
4. Neither would enter the egg.
5. Cannot predict which of the above would most likely occur.

(The information relevant to this question that was available to students from lecture is shown in the boxed section on the opposite page.)

We thought this was a very simple problem to solve based on information provided in the lecture. Much to our surprise, the success rate on the question was only slightly higher than 20%—barely above the chance level! In an attempt to discover why performance had been so poor, the next day we individually asked several of our best students why they had

The primary purpose of this monograph is to give teachers practical techniques and procedures that can be applied to help students achieve significant improvement in thinking skills.

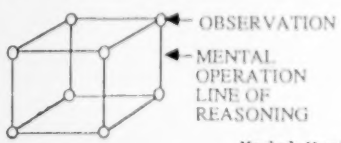
missed this question. In every case, the response was the same: "I tried to remember what you said would happen when two sperm attempted to enter an unfertilized egg at the same time. I couldn't remember so I just guessed."

The results clearly showed that the students had "just guessed." We were devastated. We certainly did not think we had been teaching students to simply recall right answers, but when faced with a simple concept analysis problem, recall was the only strategy they attempted.

This classroom experience occurred more than 20 years ago and set us on a course to discover teaching strategies to improve critical thinking. Our efforts have led us to develop, examine and evaluate a variety of techniques that could prove useful.

The techniques recommended in this monograph and our instructional strategy are based on the two models that follow. Instructors and textbooks alike often define biology as the study of life or the science of life. We define biology (see diagram below) in the form of a matrix of observations held together by mental operations or lines of reasoning. This matrix has no boundaries; as the number of observations increase or when new lines of reasoning are formed, our understanding of biology increases. This model therefore takes into account the increase in the knowledge base of Biology and the expansion of biology textbooks.

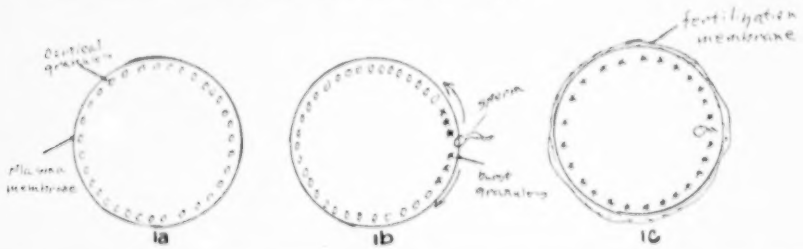
WHAT IS BIOLOGY?



Model Number 1

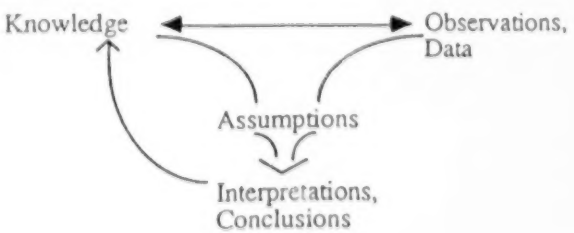
Fertilization

Just inside the plasma membrane of the unfertilized frog egg are small structures termed cortical granules (Figure 1a). When a sperm cell penetrates the plasma membrane, this entry appears to initiate the bursting of the cortical granules. This bursting reaction spreads across the surface of the egg from the point of entry (Figure 1b) and takes about 20 seconds to reach the opposite side of the egg (Figure 1c). As cortical granules burst, a thick fertilization membrane is formed on the surface of the egg and does not permit the entry of a single sperm, an impenetrable fertilization membrane is formed surrounding the egg.



As important as the scientific method is, this method is not a very effective model for the thinking processes utilized in critical thinking. One that we have found to be more descriptive and realistic is shown in the diagram below:

Critical Thinking Model
Most simplified form.



Note
1. Initial and entry position of knowledge.
2. Interaction between knowledge and observations.
3. Presence of assumptions.
4. Distinction between observations and interpretations.
5. Conditional nature of interpretations.

Note that the starting point for this process in the upper left hand part of the diagram is existing knowledge held by the

student. This knowledge may include misconceptions, preconceptions and incorrect information, as well as accurate content information. The interaction between knowledge and observations is shown by the two-headed arrow indicating that existing knowledge strongly influences the observations made and the results attended to by a student.

A key feature of the model is the central position of assumptions. Chapters 2 and 3 provide an in-depth discussion of the role of assumptions and nature of student difficulties.

The diagram as a whole emphasizes that both assumptions and logical arguments are the activities which link existing knowledge of the student and observations, data, or results to a conclusion. Once this conclusion is reached, it is incorporated into the student's store of existing knowledge. It is important to recognize that the scheme is highly dynamic with constant change occurring in all components. Continuous change takes place in the existing knowledge store with successive cycles through the process. As the knowledge base changes, the nature of the operations in the rest of the process is also altered. The dynamic aspect is often difficult for students and teachers to recognize. Indeed, it is more comfortable to deal with a static, relatively constant system, but the nature of critical thinking activities argues against such a view. Utilizing the concepts in these models, we have developed techniques and exercises that will build students' critical thinking skills.

What do we want our students to do? How can we develop their critical thinking abilities? Obviously the recommendations by professional associations strongly encourage understanding beyond the memory/recall level. While there are many proposed definitions and taxonomies for critical thinking, the classroom biology teacher would probably accept the following as important critical thinking skills within the context of biology:

- Apply biological concepts to solve new problems.
- Evaluate evidence with regard to specific hypotheses.
- Make predictions and support these with sound arguments.
- Evaluate experimental designs.
- Identify alternative interpretations of data and observations.
- Identify critical assumptions.
- Interpret experimental data and draw valid conclusions.

Defining the key terms in this list is fairly simple:

1. *OBSERVATION* - an act of recognizing and noting an occurrence often involving measurement with instruments.
2. *HYPOTHESIS* - a tentative explanation for some observation or phenomenon which can be tested.
3. *INTERPRETATION* - explanation, the act or result of interpreting. To tell the meaning of or present in understandable terms.
4. *CONCLUSION* - a reasoned judgment based on evidence.
5. *PREDICTION* - a forecast. To foretell on the basis of observations, experience or scientific reason.
6. *INFERENCE* - the act of process of inferring: as the act of passing from one proposition statement or judgment considered as true to another whose truth is believed to follow from that of the former.
7. *ASSUMPTION* - the supposition that something is true. A statement taken for granted without evidence.

With little effort, this list could be greatly expanded, but listing and defining are relatively simple tasks. A much more demanding effort is to devise teaching techniques, strategies and materials that will develop these critical thinking skills and abilities in our students.

In our experience over the past 20 years researching critical thinking, developing instructional material, and classroom teaching to foster thinking skills, the most important factor in developing students' skills is consistent, effective practice with the specific skills listed previously, coupled with good coaching. It must be recognized that effective practice is not memorizing more information, more detailed note taking or reading a more detailed textbook. Neither is good coaching with more detailed lectures or covering the material in more "depth." Unfortunately, students often view memorization as the learning strategy of choice and consider memorization of more and more information as the primary indicator of better learning. Teaching methods and materials must be developed to move students away from this unproductive strategy and to more clearly emphasize thinking skills.

As with any other skill such as writing ability, ballet dancing or shooting a basketball, proficiency improves with consistent practice, determination, learning from mistakes and persis-

tence. Critical thinking is a mental, intellectual skill where practice is equally essential.

The coaching must be provided by you, the teacher. While students could develop acceptable abilities due solely to their own efforts and judgments, good coaching as described in the rest of the monograph will greatly accelerate this process.

How Can You Provide Effective Practice & Good Coaching?
Two factors are of overriding importance:
• Providing appropriate classroom interactions
• Conducting practice activities and exercises that engage students individually to provide both in-class and out-of-class practice. The teacher's role will be to manage the classroom activities and to provide feedback on the practice exercises.

Before examining how to successfully implement effective teaching and learning practices, it may be helpful to consider what should not be done to teach thinking skills. Several common mistakes are made when teachers first attempt to develop critical thinking skills. Some of these are described below and should be recognized as unproductive strategies.

1. Attempting to teach critical thinking and rectify critical thinking difficulties by simply providing more information.
It is tempting to think that if students just had enough content information they would then be able to analyze and solve problems.

Far more likely, however, is that your students do not know how to apply and utilize the information they have. Building a line of reasoning, distinguishing evidence from opinion and identifying assumptions require repeated practice in every biology content area. Indeed, students themselves will often provide false clues about their difficulties. They tend to attribute their failure to an inability to remember enough information, and teachers often try to help by giving even more (unneeded) information.

2. Failing to maintain a constant emphasis on critical thinking.
Too often courses and textbooks start with an introductory section on scientific method that describes the process of science but thereafter little, if any, attention is given to interpretation, drawing conclusions or evaluating evidence. Many textbooks provide no examples of experiments in specific content chapters and give few, if any, presentations of data to be analyzed. Questions at the end of chapters require only the recall of information. Considering that many teachers use the textbook as a guide to the way they teach, this can be seriously misleading to teachers. To be effective, examples and critical thinking exercises should be used throughout the course.

Merely introducing the processes and then focusing only on "facts" will do little to develop students' skills. This is the approach practiced almost universally and its failure rate is well-documented.

3. Giving the "answer" first before considering experimental results or investigation.
Frequently teachers want to explain a phenomenon or concept before considering appropriate questions, hypotheses or evidence. There is little indication that scientists ask questions, formulate hypotheses and perform experiments. This can create the impression that somehow scientists know the answer and that experiments are simply done to confirm what is known to be true.

4. Assuming that critical thinking can be developed only through extensive class discussion.
While class discussion is certainly appropriate with some topics, it is not a requirement for developing critical thinking. Extensive discussion can take an inordinate amount of class time and detract from the attention given to concepts that must be covered. It is no substitute for well-designed instruction focusing on critical thinking.

5. Limiting critical thinking activities to rather grand, complex issues.
There is often the assumption that developing critical thinking requires consideration of an overly broad issue such as, "What will be the effect of an AIDS epidemic on health care costs and social legislation?" Such complicated topics, however, probably do little to develop thinking skills at the introductory level. Students have enough difficulty dealing with much more sharply focused analytical exercises; how can they be

expected to develop their skills from such broad considerations?

6. Giving exam/homework questions or exercises without providing prior preparation.
Many teachers can relate an experience where they have included a "thought" question or analysis exercise on an exam "just to see how the students would do." This experience usually involves disappointment with student performance, surprise at what is often a negative emotional response, and future aversion by teacher and students.

Without practice and preparation, however, students do not know how to deal with such exercises and are likely to view them as "trick questions" that are "not fair." Students do require practice to develop their ability to analyze critical thinking exercises.

7. Impatience.
Thinking skills develop slowly. Students do not learn skills such as good writing in a few lessons; nor will they develop good thinking skills quickly. Do not expect too much too soon.

There are, however, effective teaching techniques and strategies that avoid these difficulties. In the chapters that follow, examples of activities and exercises will be provided as well as indications of student and teacher difficulties. Before addressing these specific topics, however, attention should be given to the basic principles of effective classroom activities and practice exercises.

REFERENCES

Norris, S. (1985). Synthesis of research on critical thinking. *Educational Leadership*, May, pp. 40-45.

National Science Foundation, Directorate for Science and Engineering Education. (1989). *Report on the National Science Foundation Discipline Workshops on Undergraduate Education.*

Sigma XI, The Scientific Research Society. (1989). *An Explanation of the Nature and Quality of Undergraduate Education in Science, Mathematics, and Engineering.*

Benchmarks for Science Literacy. Part 1: Achieving Science Literacy. (1993). Washington, DC: American Association for the Advancement of Science.

Chapter Two

Instructional Strategies

In addition to the recommendations of professional associations discussed in Chapter 1, the development of strategies for teaching thinking skills is strongly influenced by views such as those of Arnold Arons (1976 & 1985). He contrasts the way science should be taught —"forwards science, idea first and name afterwards"— with the more traditional method of science teaching—"backwards science" or the interpretation/answer given first and then supported with confirming observations. Arons argues that backwards science is clearly not the way science is done or understood and "carries for the student the clear implication that there existed an *a priori* reason for the phenomenon—a reason the scientist had long ago discovered and that the student himself might also have known had he had the proper revelation." In other words, there is no clear perception by the student that "answers" (interpretations/conclusions) originate with observations and experimental evidence that are then interpreted with a logical line of reasoning. If students see no need to utilize thinking skills to arrive at "answers," then they are not likely to practice or develop such skills.

Arons argues that students and teachers should constantly examine questions such as: "How do we know . . .? Why do we believe . . .? What is the evidence for . . .?" He points out that:

> "The great majority of our students have accepted these propositions [conclusions or 'facts' of science] on faith. They have almost never examined evidence or articulated in their own words any of the reasons that lead us to hold these views. They received them as end results from authority and pass them on to others in exactly the same manner. Eventually it does become necessary to take some end results of scientific inquiry on faith; we cannot develop extensive evidence in every single area we wish to study or interrelate. The students, however, have never discriminated between assertions such as, 'scientists know that . . .' and instances in which they have followed at least some of the evidence and understood how the particular result was validated and accepted. Before submerging them in further assertions of end results, it is essential to lead them to an understanding of the basis for some of our most fundamental and far reaching ideas."

Moreover, Arons argues that students must be presented with the "idea first and name afterwards" as he indicates:

> "The students we encounter have virtually no sense of the fact that words acquire meaning and communication becomes possible only through elements of shared experience. They almost invariably hold the unproved assumption that knowledge and understanding reside directly in the technical terms they have learned."

With the strong traditional emphasis in biology on terminology and vocabulary, Arons' argument is particularly appropriate.

How do these recommendations and observations by Arons and by professional associations translate into teaching practice? How can we, as teachers, deal with student misunderstandings and provide useful instruction?

What Should We Do?

With these recommendations in mind, several specific teaching strategies can be suggested. As practical guidelines that can be directly applied in the classroom, we have found that the following approaches and techniques are effective:

1. Introduce topics with questions and observations (as a natural entry into a new topic) that are both more easily understood by students and more descriptive of real science.

- "How would you expect the concentration of CO_2 and O_2 to differ in inhaled and exhaled air?"
- "Look at these data on the concentration of CO_2 and O_2 in inhaled and exhaled air. What are your observations?"

Such questions are a logical starting point for examining a new topic. Further questions can be continually raised as a subject is being studied. Many questions can be posed by the teacher without expecting students to suggest answers, but to indicate the kinds of questions that can and should be asked. They also illustrate a way of thinking and studying a new subject—study and learning proceeds by asking useful and informative questions and seeking logical answers, not by memorizing information.

2. Use real data and examples to illustrate and develop concepts. Ask students for their observations, then their interpretations. [Students often confuse observations with interpretations. Based on our experience, they must be constantly guided to contrast the two.]
Observation: "Look at this time-lapse film of a cell undergoing mitosis. What do you see?
Interpretation: "How would you explain (interpret) this observation? When the new cell entered interphase, each chromosome was a single strand (monad). Yet when this same cell later entered prophase, each chromosome was double-stranded (dyad)."

Students have a strong tendency to state an interpretation and claim that that is what they observed. For example, many students observing the mitotically dividing cells will maintain that they "saw" equal amounts of DNA distributed to the daughter cells. They can be clearly guided to recognize that they observed only chromosome movements. An interpretation/conclusion about equal amounts of DNA involves additional knowledge about chromosome composition and assumptions about the distribution of DNA within the chromosome.

Much of this problem most likely resides in the way textbooks present information; few, if any, examples are provided of observations or data leading to interpretations. Instead, information is presented as statements of fact. As Arons stated earlier, students should have the opportunity to follow at least some of the evidence to reach a conclusion even though we cannot provide extensive evidence on every topic.

3. Draw student's attention to critical assumptions.
"The logarithmic growth curve assumes there is no cell death and generation time is constant. Suppose these assumptions were not realistic, what would the curve look like?"

Identifying and dealing with assumptions is the most difficult task for students. Perhaps this is because assumptions seem to run counter to good science. As statements that must be accepted as true with no evidence in order to make a specific interpretation, assumptions represent a high degree of uncertainty. Admitting the existence of assumptions acknowledges uncertainty—a situation most students wish to avoid.

Moreover, textbooks seldom draw attention to assumptions and even less frequently provide exercises for students to gain skills in identifying assumptions. Thus, students have no practice and develop little skill.

4. Use existing concepts to explain and interpret new observations. "Observations show that the DNA content per cell when the cells enter mitosis is twice the DNA content/cell when cells have completed mitosis. How is this consistent with chromosome movements during mitosis?"

Concepts and terms should form an interrelated network for students, not isolated and independent bits of information. Repeated and varied applications will lead students to construct a coherent, logical structure of biology. By interrelating and continually applying concepts, students build familiarity with both terms and concepts, and are able to utilize these more effectively.

Unfortunately, students all too easily fall into the habit of "learn and forget." Indeed, instruction and textbooks are frequently organized so that concepts once covered are little utilized later in the course.

5. Make predictions based on appropriate concept applications. "Suppose the number of carnivores were decreased in this ecosystem. What predictions would you make about the change in numbers of consumers and producers?"

Predictions are another opportunity for students to apply concepts and test their understanding. In addition, predictions suggest further tests of interpretations that can be used in additional investigations.

These strategies clearly indicate that the teacher should constantly illustrate and apply the activities of interpretation, observation, identification of assumptions, prediction and concept application. The questions raised by the teacher serve to engage the students in the activity and provide practice. The teacher is constantly modeling and illustrating the

thinking skills students are expected to develop.

For most teachers, such classroom strategies will not require any sweeping revisions, but can be accomplished with simple reorganization and sequencing of presentations and with the inclusion of carefully selected questions, examples and applications.

A useful aid to planning and structuring classroom presentations is to identify specific examples that illustrate observations, interpretations, assumptions and predictions. The following outline can be used to describe these components:

Situation
Observations
Interpretations
Assumptions
Predictions

By preparing numerous examples, teachers will be able to generate highly useful material for use in their classes. Utilizing at least one example per class will add a major emphasis on thinking skills. Several examples follow:

ENZYME EXAMPLE

Situation: Yeast cells are ground up to release the yeast cell contents. This material was filtered using a coarse filter to remove solid particulate material. The remaining extract was cloudy liquid. A few drops of this liquid were added to a flask containing a pure sucrose solution.

Observations: In the flask with added yeast extract, glucose concentration began to increase. In a control flask with no added yeast extract, no glucose could be detected.

Interpretations: An enzyme was present in the yeast extract catalyzing the breakdown of sucrose into glucose and fructose.

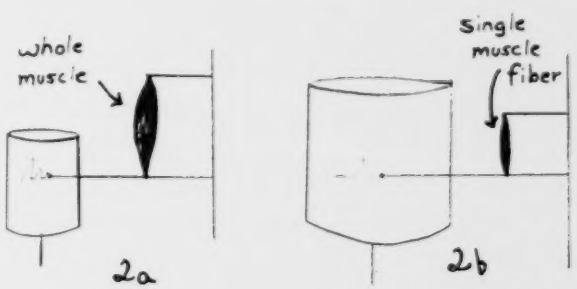
Assumptions:
1. Grinding yeast cells does not damage sucrose-digesting enzymes.
2. Filtering does not remove sucrose-digesting enzymes from the extract.
3. Glucose was not present in the yeast extract.

Predictions:
1. If the experimental flask is sampled at increasing periods of time, an increasing amount of glucose will be found.
2. If the yeast extract is boiled before adding to the sucrose solution, then no glucose should appear when yeast extract is added.
3. If the yeast extract is diluted before adding to the sucrose solution, then glucose will appear more slowly.

By arranging examples in this way, the teacher can insure what appropriate observations, interpretations, assumptions and predictions are specifically identified and included in the lesson plan.

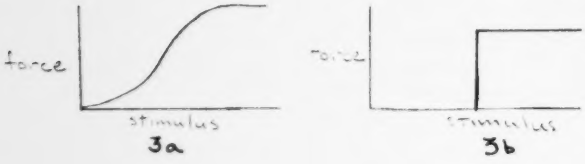
PHYSIOLOGY EXAMPLE

Situation: A whole muscle, composed of many single muscle fibers or cells, is removed from a frog's leg and is stretched in the apparatus shown below (Figure 2a). A single muscle cell can be removed from a whole muscle and stretched in the same way (Figure 2b).



Observations:* When the whole muscle is stimulated with an increasing electrical stimulus, the contraction increases gradually until a constant strength of contraction is reached (Figure 3a). When the single cell is stimulated

with an increasing stimulus, no contraction occurs until a minimum, threshold stimulus strength is reached. At higher stimulus strengths, the force of contraction is constant (Figure 3b).



3a 3b

*Data from: Baker, J.J.W. & Allen, G.W. (1972). *The Study of Biology (2nd ed.).* Reading, MA: Addison Wesley Publishing Company. Used with permission.

Interpretations:
1. Different muscle fibers comprising the whole muscle have different thresholds.
2. All the individual muscle fibers in the whole muscle are contracting when the muscle reaches maximum contraction.

Assumptions: When the muscle is stimulated, the same stimulus strength is transmitted throughout the whole muscle.

Predictions: At stimulus strengths greater than those shown in Figure 3a, the force of contraction will not increase.

ECOLOGY EXAMPLE

Situation: In an area of North American woodland, all the organisms were counted during a short period in the summer. These organisms were categorized in terms of their food or energy source.

Observations:**
Producers (trees and other green plants) = 200
Primary Consumers (such as leaf-eating insects) = 150,000
Secondary Consumers (such as birds that consume insects) = 120,000
Tertiary Consumers (such as hawks that eat birds) = 2

Interpretations:
1. A few large producers (such as trees) can provide sufficient food for a much larger number of small consumers (such as leaf-eating insects).
2. Many secondary consumers (such as birds) are required to provide sufficient food for larger tertiary consumers (such as hawks).

Assumptions: Organisms did not move in or out of the area while counts were being made.

Predictions:
1. In an area with smaller producers (such as a grassland), producers should outnumber the primary consumers.
2. In winter, the number of primary consumers should drastically decrease.

**Data from: Odum, E.P. (1971). *Fundamentals of Ecology (3rd ed.).* Philadelphia: W.B. Saunders Company. Used with permission.

One concern teachers may have is that a questioning strategy used with these examples can take too much time—there is a great deal of material to cover, and having students attempt to answer too many questions will require an excessive amount of class time. We have found, however, that with appropriate classroom management by the teacher, an acceptable pace can be maintained. (See Chapter 4 for examples.)

It must be recognized that these strategies are not a "discovery" or "inquiry" mode of instruction where students are required to formulate their own conclusions in every case. Instead, the

The Comparative Class Presentation on Respiration can illustrate the critical importance of sequencing including important questions.

questions represent points of emphasis for the teacher to guide and illustrate the scientific process for students. Students should be given the opportunity to respond, but if their comments are awkward or off the point, the teacher should give immediate feedback and carry the interaction forward to the desired end.

The following illustration of two ways to handle a classroom presentation can show the critical importance of sequencing and including important questions. This example shows only the key interactions and sequencing of the presentation; much of the description and discussion that would be part of a typical class are not shown.

Comparative Class Presentation on Respiration

Traditional or Descriptive Approach

The subject for today is respiration which is the process of exchanging oxygen and carbon dioxide between the body and the external air.

The structure of the respiratory system shows that air enters the trachea, branches into the bronchial tubes leading to each lung, and ends in alveoli which are in close contact with blood vessels.

Oxygen diffuses out of the alveoli into the blood, and carbon dioxide leaves the blood and enters the alveoli.

Analytical Approach
(Designed To Develop Critical Thinking Skills)

What happens to the air we breathe? Look at these data. What observations can be made?

Gas	Inhaled Air	Exhaled Air
Oxygen	19.7%	15.7%
Nitrogen	74.1%	74.5%
Carbon Dioxide	0.04%	3.6%

What conclusions can be drawn from these data?

The structure of the respiratory system shows that air enters the trachea, branches into the bronchial tubes leading to each lung, and ends in alveoli which are in close contact with blood vessels.

If air were sampled at each of these locations in the respiratory system, what gas compositions would you predict?

Look at these data on alveolar air:

Gas	Composition
Oxygen	13.6%
Nitrogen	74.9%
Carbon Dioxide	5.3%

(Comparative Class Presentation on Respiration Continued)

How do these data compare with those in the first table? Why is the alveolar gas so different from the inhaled air?

The exchange of oxygen and carbon dioxide indicate that blood entering the lung is low in oxygen and high in carbon dioxide, while blood leaving the lung is high in oxygen and low in carbon dioxide.

Since the alveoli are in close contact with blood vessels, perhaps gasses are entering and leaving the blood at this location. If this is so, what differences would you predict between blood entering and leaving the lung?

Look at these data:

Blood Gas Composition

	Oxygen	Carbon Dioxide
Entering Lung	5.3%	5.9%
Leaving Lung	13.7%	5.3%

The following data illustrate this process of gas exchange:

Exhaled Gas	Inhaled Air	Air	Alveolar Air
Oxygen	19.7%	13.6%	15.7%
Nitrogen	74.1%	74.9%	74.5%
Carbon Dioxide	0.04%	5.3%	3.6%

Results from blood gas measurements also show the expected changes.

Blood Gas Composition

	Oxygen	Carbon Dioxide
Entering Lung	5.3%	5.9%
Leaving Lung	13.7%	5.3%

In summary, the data indicate that oxygen moves from the alveoli into the blood, while carbon dioxide moves from the blood into the alveoli and is exhaled. What does this interpretation assume about loss of oxygen and gain of carbon dioxide in parts of the respiratory system other than the alveoli?

The critical thinking approach includes all the recommendations listed previously:
- Start with questions.
- Clearly illustrate and contrast observations and interpretations.
- Use established concepts to draw conclusions and make predictions.
- Draw attention to assumptions.
- Use data and experimental results to lead to conclusions.

This approach is structured to proceed in a scientific manner from question to data to conclusion.

The more traditional approach, on the other hand, is descriptive and explanatory. Data are included almost as a secondary factor to illustrate the description. Nowhere are conclusions, observations, interpretations, assumptions or predictions mentioned.

Actually this comparison does not indicate as great a contrast as probably exists in reality. In our illustration of the traditional presentation, data on gas composition were included. The far more typical situation is to include no data or experimental results but to rely solely on description. Indeed, almost all textbooks are devoted entirely to description with extensive definition of terms. Little, if any, data are included. Teachers who use the textbook as the primary guide for their teaching presentations (and most do) will have little support for a presentation on thinking skills.

A great deal can be accomplished with appropriately planned and organized lessons. Perhaps more important, however, is student practice with sharply focused exercises designed to develop critical thinking skills. Several examples of such exercises are given in the next chapter. These exercises can be a worthwhile and productive addition to classroom presentations, but are probably more useful in extending practice to homework activities.

REFERENCES

Arons, A.B. (1976). Cultivating the capacity for formal reasoning: Objectives and procedures in an-introductory physical science course. *American Journal of Physics, 44*(9), pp. 834-838.

Arons, A.B. (1985). "Critical thinking" and the baccalaureate curriculum. *Liberal Education, 71*(2), pp. 141-157.

Chapter Three

What Is Effective Practice?

The time spent in developing critical thinking skills in classroom and laboratory interactions is essential. This time, however, is limited. If students are to progress, their effective practice of/with thinking skills must be extended beyond the classroom. Such practice can be provided with exercises designed to engage students in the application of thinking skills.

In this chapter, three kinds of exercises are described. All of these emphasize writing as an effective component of practice. The process of writing is extremely important since it serves to clearly focus the student's thinking and analysis on the exercise. Writing forces the student to be an active, individual participant in a more meaningful way than listening, reading or even note taking.

Effective exercises also focus the student on specific, clearly defined tasks. In contrast to essay questions, which are often rather general and allow students to write extensive, descriptive information without demonstrating analysis, critical thinking exercises must be specific and focused. Useful exercises present the student with new applications requiring the solution of unfamiliar and challenging problems.

The following sections describe three kinds of exercises that share these characteristics.

I. Multiple-Choice Written Exercises

One type of exercise that has proven highly beneficial to students is a modified multiple-choice question. In contrast to most multiple-choice questions, however, which focus on memory/recall, these exercises are written to require concept application to new situations, identification of assumptions and other thinking skills. Students are required to write out their arguments for accepting or rejecting each choice and thus practice constructing lines of reasoning while directly applying concepts.

A unique feature of these exercises is that students are required to write separate arguments for choices which are rejected as well as arguing for the accepted choice. If the choices are carefully constructed, students will be forced to evaluate subtle distinctions that would be seldom made in an open-ended essay question. It is extremely important that students write clear, complete reasons for accepting or rejecting each choice. The process of constructing, evaluating and revising their rationale for the choices is the major focus of the practice in these exercises.

Statkiewicz and Allen (1983) have shown that practice with such exercises will significantly improve critical thinking skills if sufficient practice and feedback are provided. A wide variety of problems and exercises covering topics in biology can be found in "Analytical Problems in Biology." The examples that follow give typical exercises as well as the kind of written analysis that should be required from students.

Example 1:

Human hemoglobin differs significantly in amino acid sequence from frog hemoglobin. When human hemoglobin messenger RNA (mRNA) is carefully injected into frog eggs, traces of human hemoglobin can be found in the eggs after one hour. From this experiment it can be concluded that:

1. Uninjected frog eggs must contain the genes for human hemoglobin.
2. The same code words (groups of 3 nucleotides on mRNA) specify the same amino acids during translation in humans as in frogs.
3. The rate of RNA synthesis (transcription) must be very high in uninjected frog eggs.
4. Human hemoglobin genes are dominant over frog hemoglobin genes.
5. All of the above conclusions are valid.

Acceptable Analysis Expected from Students:

1. Genetic information in DNA is not required in this case since mRNA has been injected and thus the genes are no longer needed to direct protein synthesis. **Reject.**
2. Since no RNA other than mRNA was infected, frog tRNA must be used in hemoglobin synthesis. The frog tRNA must (with appropriate amino acids attached) be matching with code words on the human mRNA. If the code words in humans and frogs differed, then the amino acid sequence would differ and human hemoglobin would not be produced. **Accept.**

3. Irrelevant. The issue here is the synthesis of a protein with the correct sequence of amino acids, not how rapidly RNA is synthesized. Whether the rate of RNA synthesis were faster or slower in uninjected eggs would make no difference in this problem.
4. Although one might intuitively think that human hemoglobin genes are dominant since they are expressed, the problem does not state that frog hemoglobin is not synthesized. More importantly, a more meaningful conclusion about the coding of information and protein synthesis in frogs and humans can be drawn from the information provided in this problem (see Number 2).
5. **Reject.** Choices 1, 3 and 4 were rejected.

Example 2:
An investigator placed five different kinds of organisms in a sealed chamber and established all conditions (such as light, temperature, water, etc.) necessary to maintain them for an extended period of time. One of the organisms was known to be a plant in which the starch had been previously labeled with radioactive carbon, and one was known to be a carnivore. A student concluded that ultimately significant radioactive carbon would be found as part of the biological molecules making up the body of all the organisms. What was the student most likely assuming?

1. The other three organisms were carnivores.
2. At least one of the other organisms was an herbivore.
3. The plant with radioactive carbon would use some of its starch in respiration.
4. At least two of the other organisms were green plants.
5. The carnivore respired more rapidly than the plant.

Analysis Expected from Students:
A necessary assumption is a statement that the student is accepting as true (with no evidence for the truth of the statement) in order to reach his/her conclusion.
1. If this were true none of the carnivores would likely contain radioactive carbon at some later time. If this were assumed, then the student would have reached a different conclusion since carnivores would not eat the plant with radioactive carbon and there would be no way for radioactive carbon to enter the carnivores' bodies. **Reject.**
2. An herbivore could consume the plant and in turn be consumed by a carnivore or carnivores. In this way, radioactive carbon could enter the bodies of the other organisms. This must be assumed if radioactive carbon is to enter the carnivore's body. **Best choice.**
3. This will probably occur and release radioactive CO_2 but would not allow radioactive carbon to be incorporated into molecules in the carnivore's body since carnivores cannot obtain carbon from CO_2. Other plants could take up the CO_2 by photosynthesis, but not carnivores. **Reject.**
4. Since carnivores do not eat plant material, assuming the other, unknown, organisms are plants would not allow the student to reach his/her conclusion. **Reject.**
5. Assuming the carnivore respired more rapidly would lead the student to a conclusion about which organism contributed more CO_2 to the atmosphere in the container. The plant would release radioactive CO_2 but this would not transfer radioactive carbon to the carnivore (see Number 3). **Reject.**

Example 3:
A plant cell is exposed to an aqueous solution having sodium and chloride concentrations higher than the sodium and chloride concentrations of the cell interior. However, after 30 minutes a student observes the cell in a microscope and states that the cell shows no evidence of having lost water. Which of the following is the best interpretation of his observation?

1. The cell membrane is not permeable to either sodium or chloride.
2. The cell has a rigid wall around it.
3. The cell protected itself by actively transporting sodium across its membrane into the external solution.
4. The plant cell, being different from an animal cell, cannot tolerate high concentrations of sodium and chloride and dies within five minutes.
5. The cell interior contains a great variety of solutes.

Analysis Expected from Students:
1. If the cell membrane was permeable to sodium or chloride, these substances would tend to enter the cell by diffusion. This would tend to compensate for any volume changes caused by water leaving the cell. But if the membrane was not permeable to these substances as stated in this choice, only

water would move and shrinkage would be evident. **Reject**, since the student apparently observed no shrinkage.
2. A rigid wall might prevent visible swelling but the cell could still shrink within the wall, leaving space observable between the cell membrane and the wall. **Reject.**
3. If the cell actively transported sodium out of itself, the concentration of water would become even greater inside and less outside the cell and the tendency to shrink from water loss would also be greater. **Reject.**
4. Whether the cell is dead or alive should not affect its permeability to water. **Reject.**
5. The tendency for water to leave the cell results from the higher concentration of water inside than outside. The presence of solutes other than sodium and chloride ions inside the cell would mean the concentration of water would be lower and the tendency for water to move out would be reduced. If the concentration of water inside was equal to that outside, the net movement of water would be zero. **Accept.**

The analysis of these exercises illustrates the kind of detail that should be expected in student arguments. Practice in evaluating and writing responses for each choice is essential to developing the desired thinking skills.

II. Analysis of Short Science Articles

In this type of exercise described by Tyser and Cerbin (1991), students read and analyze relatively short articles of 6 - 12 paragraphs from a newspaper or popular science magazine. The intent of these exercises is "to become proficient at writing logically persuasive responses to claims made about newspaper and magazine science articles. The exercises are meant to help [the student] think critically about meaningful science issues [the student] will encounter throughout life."

Line of Reasoning (LOR) Model - Before attempting any analysis of a science article, students are provided with the Line of Reasoning Model shown in Figure 4. This model provides a clear and obvious scheme for evaluation of claims and statements found in the article.

Students practice using the Line of Reasoning Model with review questions that emphasize the identification and evaluation of inferences and evidence. These examples and questions, more simple than the articles, provide a useful introduction to the more demanding analysis of a science article. The review exercises that follow are typical of those provided to students.

Review Exercises

1. What is an inference?

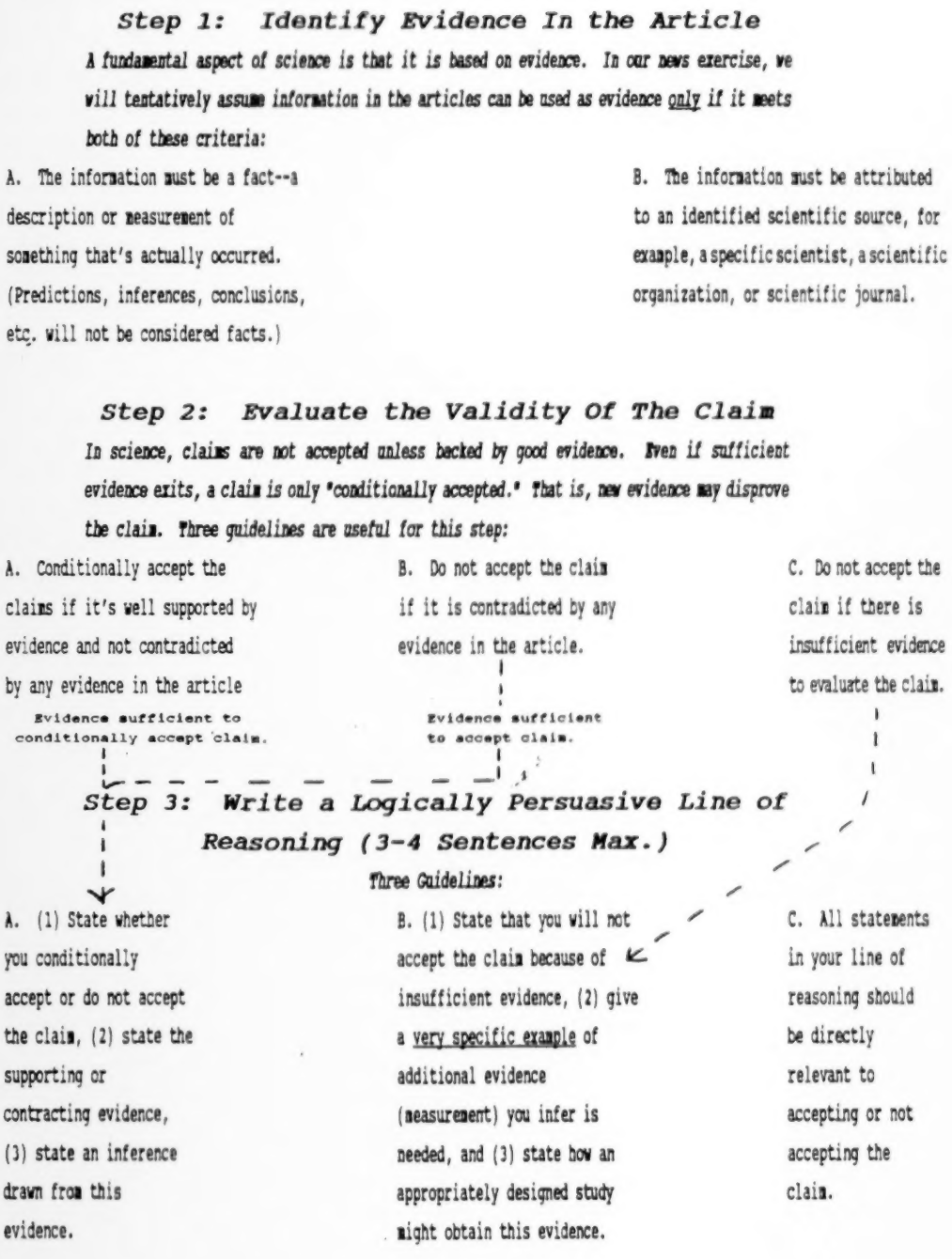
2. What if most of the evidence presented in an article supports a claim, but some does not? From a scientific perspective, can this claim be conditionally accepted? (Carefully consult the guidelines in Step 2 of the LOR model.)

3. In each of the following examples, draw a solid line beneath the statement with the evidence, and draw a dotted line under the statement with the inference.
- Information in the article stated that air pollution is higher in urban areas than in nonurban areas. Thus one would expect to find more respiratory illnesses in urban areas.
- One can't determine yet if fluoride causes certain kinds of bone cancer until more testing is done. According to the article, only 20 animals were used in the study.
- The study showed that fossils of organisms in the kingdom Monera are much older than are fossils of the other kingdoms. A reasonable conclusion is that the kingdom Monera was the first kingdom to evolve on this planet.

Imagine that you recently graduated from college with a degree in Elementary Education. You've been hired by a nearby school district. Because you're new in the district and want to meet more of your fellow teachers, you volunteer to serve on a committee of teachers and school administrators. This committee is to propose a new science education curriculum for your school district.

The school Superintendent sends you a report published by a national task force of professional educators and scientists assessing the state of science education in the United States. The agenda for the first committee meeting is to discuss the report. Below are some comments made by committee members at this meeting. The Superintendent asks committee members to prepare brief written responses about issues

Figure 4. Line of Reasoning Model.


Step 1: Identify Evidence In the Article
A fundamental aspect of science is that it is based on evidence. In our news exercise, we will tentatively assume information in the articles can be used as evidence only if it meets both of these criteria:
A. The information must be a fact--a description or measurement of something that's actually occurred. (Predictions, inferences, conclusions, etc. will not be considered facts.)
B. The information must be attributed to an identified scientific source, for example, a specific scientist, a scientific organization, or scientific journal.
Step 2: Evaluate the Validity Of The Claim
In science, claims are not accepted unless backed by good evidence. Even if sufficient evidence exits, a claim is only "conditionally accepted." That is, new evidence may disprove the claim. Three guidelines are useful for this step:
A. Conditionally accept the claims if it's well supported by evidence and not contradicted by any evidence in the article
B. Do not accept the claim if it is contradicted by any evidence in the article.
C. Do not accept the claim if there is insufficient evidence to evaluate the claim.
Evidence sufficient to conditionally accept claim.
Evidence sufficient to accept claim.
Step 3: Write a Logically Persuasive Line of Reasoning (3-4 Sentences Max.)
Three Guidelines:
A. (1) State whether you conditionally accept or do not accept the claim, (2) state the supporting or contracting evidence, (3) state an inference drawn from this evidence.
B. (1) State that you will not accept the claim because of insufficient evidence, (2) give a very specific example of additional evidence (measurement) you infer is needed, and (3) state how an appropriately designed study might obtain this evidence.
C. All statements in your line of reasoning should be directly relevant to accepting or not accepting the claim.

BEST COPY AVAILABLE

discussed in the meeting.

4. The Superintendent starts the meeting and then makes this claim, "U.S. students are much less scientifically literate than students in many other developed countries." You do recall a table in the task force in the report showing that U.S. student science test scores rank 10th compared to other developed countries. Thus, this table presented facts having a credible scientific source.

You write, "I will conditionally accept this claim. It is supported by evidence that our students' test scores are only 10th compared to other developed countries. This suggests that U.S. students are less scientifically literate."
a. Which guideline in Step 2 was used? A B C
b. Which two guidelines in Step 3 were used? A B C

5. Mr. John Doe from Snodgrass Middle School brown-noses, "I couldn't agree with you more Mr. Superintendent." He then claims, "That's probably because other countries use more innovative teaching techniques." You have read the report thoroughly and remember that it presents observations from a scientifically valid study clearly contradicting this claim.

You write, "I can't accept this claim. Evidence in the report states that many of these countries use "old-fashioned" teaching methods, including traditional classroom lecturing. This implies that their teaching methods are not particularly innovative."

See "a" and "b" in Exercise 4.

6. Ms. Jane Dough, from Memorial High, later claims, "U.S. students have poorer critical thinking skills compared to students in other countries." But you're positive that no observations or measurements either supporting or contradicting Jane's claim were ever presented in the report.

You later write, "I can't accept this claim because of insufficient evidence. We need evidence about how students reason and evaluate scientific problems. This evidence could be obtained by comparing responses to questions requiring critical thinking given to students that have been matched for age and socioeconomic status but that differ in nationality."

See "a" and "b" in Question 4.

Science Articles

During a typical semester students are required to analyze six or seven articles provided by the instructor. The following examples describe two of these assignments as well as the questions for each article.

Example 1:
OZONE HOLE THREATENS POLAR PLANKTON

Rapidly accumulating evidence shows that man-made CFCs are responsible for the seasonal ozone holes appearing over the North and South Poles. What is less clear is the effect that ozone depletion—and the subsequent increase in UV light penetrating the atmosphere—has on living organisms in the pole regions.

It now appears that elevated levels of ultraviolet light filtering through the winter "hole" in the stratospheric ozone layer above Antarctica threaten tiny plants that feed, directly or indirectly, virtually all other polar life, according to oceanographer Sayed El-Sayed at Texas A & M University in College Station. His studies at Antarctica's Palmer Station show the photosynthetic capacity of marine phytoplankton (one-celled algae) at the bottom of the polar food chain is extremely vulnerable to the increases in ultraviolet (UV) light that accompany the ozone hole detected annually over the Antarctic since the late 1970s.

In a series of experiments, El-Sayed measured the photosynthetic rate of polar phytoplankton housed in adjacent tanks and exposed to four different UV conditions. Ambient (natural) light, which contains low levels of UV light, irradiated the one-celled organisms in the first tank. Plexiglas filters eliminated all UV light from the second tank. Filters screened out about one third of the ambient UV from tank three. And fluorescent UV lamps augmented natural solar-UV irradiation by about 16 percent in the fourth tank, conditions meant to simulate what might occur under an ozone hole.

Compared to phytoplankton raised under ambient light, those exposed to the enhanced UV reduced their photosynthetic rate 35 - 75 percent—depending on the source of the tiny plants (open water, ice or a sea-ice hole). By contrast, those exposed to just two-thirds of the normal UV increased their photosynthetic rate from 35 - 175 percent. Those in the UV-free tank boosted their photosynthetic rate a dramatic five- to seven-fold.

These data "are very consistent with our results, says Osmund Holm-Hansen at the Scripps Institution of Oceanography in La Jolla, California. He says they show that where the light intensity is high—as it is in the upper one or two meters of the ocean—"natural UV levels are having a very dramatic effect," substantially reducing the productive capacity of these plants. Less clear, he says, is whether UV effects are as potent in the ocean's darker, deeper reaches.
[Source: Science News, 1989, Vol. 136]

Article Questions

1. Summarize the biological events being studied or alluded to in a three-step cause/effect sequence. Part of this sequence has been summarized already.

CFC levels	causes ——? increase	causes ——	more UV penetrates atmosphere	causes ——?	

2. The independent variable in this experiment was the amount of _____.

3. A variable that should be controlled in this experiment was the amount of _____.

4. Find this sentence in the article, "His studies at Antarctica's Palmer Station show the photosynthetic capacity of marine phytoplankton (one-celled algae) at the bottom of the polar food chain..." It doesn't qualify as evidence because it doesn't meet one of the evidence criteria in Step 1 of the LOR model. Which criterion, A or B, is not met?

5. Now find this sentence, "Compared to phytoplankton raised under ambient light, those exposed to the enhanced UV reduced their photosynthetic rate 35-75 percent..." Which criteria do information in this sentence meet? Circle the appropriate criteria (just A, just B, or both): A B
Thus, does the information in this sentence qualify as evidence? _____

6. Consider other sentences in the article. State one specific bit of information that meets both evidence criteria:

Example 2:
GENETIC TESTING POSSIBLE BEFORE CONCEPTION

It wasn't so long ago that a woman had to wait until her child was born before she knew whether it suffered from some genetic defect. Amniocentesis and, more recently, chorionic villus sampling have changed that, making genetic testing possible after only eight weeks of gestation. And newer techniques suggest that artificially inseminated embryos only a few hours old—as small as the eight-cell stage—may reveal their genetic abnormalities in the petri dish before being transferred to a mother's womb, allowing her to decide whether or not to proceed with the implantion.

Research now suggests that genetic testing may soon become feasible even in unfertilized eggs—clearly before conception. While such tests cannot evaluate the father's genetic contributions, they could prove valuable for women at high risk of giving birth to a child with a severe genetic defect.

So far, Yury Verlinsky and his colleagues at the Illinois Masonic Medical Center in Chicago have performed the sensitive analytic technique on eight eggs from one mother known to harbor a defective gene. Of the five eggs successfully tested, two came up negative for the defective gene and were implanted in her womb following *in vitro* ("test-tube") fertilization. Although the woman did not become pregnant,

the researchers say the testing technique worked well and appears not to have been a factor in the unsuccessful implantation. *In vitro* fertilization attempts typically have high failure rates.

To perform their analysis, the researchers took advantage of a natural quirk of egg production. While most human cells contain 46 chromosomes (23 from each parent), egg and sperm cells contain only half that number. During the specialized cell division that leads to the creation of egg cells, the leftover complement of 23 chromosomes gets packaged into a smaller cell called a polar body, which remains attached to the egg but eventually wastes away. In a woman who has inherited a normal gene from one parent and a defective version of the same gene from the other parent, the question of which gene her child will inherit boils down to one random event: Will the good gene end up in the mother's egg cell, or in that egg cell's polar body?

Direct tests on the egg would destroy that cell. So, after retrieving several eggs from the woman's ovary, Verlinsky and his co-workers carefully removed each egg's polar body and performed sensitive genetic tests on these. When the polar body harbored the normal gene, they knew the egg contained the abnormal one. When the polar body contained the abnormal gene, the researchers fertilized the corresponding egg with the husband's sperm and implanted the young embryo in the woman's uterus.

"This circumvents the possible need for elective termination" of pregnancy, Verlinsky said at the annual meeting of the American Society of Human Genetics in Baltimore. He predicts the technique will prove useful for a variety of recessive inherited defects such as cystic fibrosis, muscular dystrophy and Tay-Sachs disease. These diseases cause essentially no symptoms in individuals carrying only one defective gene but can kill when defective genes are inherited from both parents. In theory, Verlinsky's technique would ensure that a child would not inherit a defective gene from both parents.

Although the procedure is time consuming and costly—adding at least $5,000 to the current $10,000 price tag for a single, standard attempt at *in vitro* fertilization—it has already stirred considerable interest among women who could benefit, the researchers say.

In related research presented at the meeting, Diana W. Bianchi of the Children's Hospital in Boston reported progress toward a method of performing genetic tests on fetal red blood cells that have leaked through the placenta into the mother's circulation. Such leaks apparently occur after about 10 weeks' gestation. The procedure, which remains experimental, requires only a blood sample from the mother's arm, making it far less invasive than amniocentesis or chorionic villus sampling.
[Source: Science News, 1989, Vol. 136]

Article Questions

1. How might you obtain evidence about the effect of maternal cigarette smoking on fetal birth defects? Assume that you will use laboratory mice to do your study. Summarize your proposed study in the work space below.

Study design:
This information could be obtained by comparing (a)_____in (b)_____ matched for (c)_____, _____, etc. that differ in (d)_____.
a=dependent variable
b=study unit
c=controlled variables
d=independent variable

Analysis of your study: What did you propose for the dependent variable, controlled variables, etc?

2. What does "*in vitro* fertilization" mean?
3. What is a polar body?
4. Why could the following statement not be used as evidence? "Newer techniques suggest that artificially inseminated embryos only a few hours old—as small as the eight-cell stage—may reveal their genetic abnormalities in the petri dish..."

5. Consider this hypothetical statement: "Evidence in the article shows that Verlinsky's procedure does not harm the egg." Why does this sentence not conform to guideline A2 in Step 3?
6. Claim: "The Verlinsky procedure is not harmful to the developing embryo."

Assume there is sufficient evidence given to evaluate this claim. Carefully using the guidelines in Step 3, write a three-sentence LOR. You'll have to decide whether the evidence supports or does not support this claim.

As a check to help see if you've written the LOR appropriately, underline where the specific evidence is with a solid line, and underline the inference you draw from this evidence with a dotted line.

7. Now consider the same claim in #9 again, but this time assume there is insufficient evidence presented to evaluate the claim.

Write your LOR, being certain all the elements of a good study design (independent, dependent and controlled variables; and study unit) are presented. I would suggest carefully following the study design format used in #1 above and on earlier handouts.

Tyler and Cerbin analyzed student responses and were able to show that practice with the Line of Reasoning Model and article questions led to highly significant improvement in students' critical thinking skills.

A similar approach is used by Rau (1991). A short article is assigned and students are required to: (1) Write a summary of the article, about 1/3 the length of the original, and (2) List three questions raised by the article. Rau found that even though some questions were naive or even nonquestions, many were excellent and demonstrated an awareness of experimental difficulties and interpretation of data.

In a second part of the assignment, questions from all students are typed on a single list. Students are then asked to categorize the student-generated questions as described here:

Categorizing the Class-Generated Questions
To the students: I have typed the questions asked by you and your classmates in response to the *Scientific American* article entitled "Pinning Down Clouds." The questions were typed just as you wrote them, with only spelling errors corrected. Lists of numbered questions have been left at the reserve desk of the library. Please obtain a copy to complete the assignment.

I would like you to consider each of the following categories:

a. An irrelevant question.
b. A question that is really answered in the article.
c. A good question, but one that is not directly pertinent to the main points of the article.
d. A question that, if answered, would lead to further discoveries.
e. A question that has an inherent error of fact.
f. A question that implies that incorrect assumptions were made by the author of the article.
g. A question that implies that incorrect assumptions were made by the researchers.
h. A question you would like to have discussed in class.
i. A question that has no scientific answer.
j. A question that is really an opinion.
k. A question that asks for a value judgment.
l. A question that could be answered by reading Chapter 13 of your textbook.
m. A question that is impossible to understand because the wording or the grammar is incorrect.

Try to find at least two examples of each. Write out the questions with its number. Explain why you believe each choice falls into the category you have placed it in.

If you wish, you may work with a classmate. If you do, find three examples of each, and submit a single report.

If you cannot find the required number of examples for a

particular category, add an additional example to one of the other categories. Also you may add a category that you have thought of that is not listed. You may use the same question for more than one category. This assignment must be typed and double-spaced.

The primary intent is to have students make and defend judgments. Rau indicates that the majority of responses are thoughtful but there is a wide range of responses. Every student, however, engages in extensive practice writing, analyzing and making judgments.

III. Case Studies

A third type of exercise is structured as a case study addressing a specific line of research or series of investigations. The emphasis is on pursuing an initial question and hypothesis via a series of predictions and experiments. Students are led to recognize that several predictions can be made from one hypothesis. Results from experiments testing the hypothesis may either support or contradict, or neither support nor contradict, the hypothesis. Results may be several alternative interpretations that can be further tested with additional experiments. Finally, support for a hypothesis becomes stronger as more predictions and tests are done.

Questions for students to answer are raised periodically in the case study, and the students are required to write out their responses. Some questions are answered within the text of the case study as examples of acceptable responses to questions. As in the previous exercises, the process of individual student analysis and writing is important to provide effective practice.

Case Study I
Lyme Disease

When a new disease is discovered, several questions are immediately asked. What causes the disease? Is it a virus or other microorganism? How is the disease spread? At first it may not be apparent that the disease is a new one, so the first question would be, "Is this a new disease?"

These questions were asked about Lyme disease when it was first observed in 1975. The first cases were in eastern Connecticut around areas known as East Lyme and Lyme. Several adults and children were reported as having symptoms characteristic of juvenile rheumatoid arthritis. Ultimately, the affected individuals developed joint problems characteristic of rheumatoid arthritis and in some patients, nerve and muscle difficulties were found. However, there were immediate indications that this disease outbreak was unusual. First, juvenile rheumatoid arthritis is rare, but in the infected areas, the occurrence was as much as 100 times what would normally be expected. Second, the distribution of affected individuals within the infected area was unusual; most victims lived near heavily wooded areas and only a few in towns away from wooded sections.

When faced with unusual conditions such as these, how do the investigators of a disease proceed? At this time, it was not obvious that a new disease was being observed but only that a disease outbreak with unusual conditions was present. Investigations proceeded with the hypothesis that this was a new disease with a distinctly different cause.

The first step in an investigation is to make extensive observations on the history of the infection in the area (i.e. when it occurs, who is infected) and the specific nature of the disease symptoms. These procedures were used in the Lyme and East Lyme areas. Several important observations were made:

1. The disease was not very contagious. Many times, an individual in a family would have the disease, yet it would not spread to other family members.
2. In most cases, the disease appeared in the summer only.
3. Many people who had the disease remembered initially having a skin rash before other symptoms appeared. The rash started as a small bump on the chest, abdomen or back and gradually expanded to cover a large area.

Since none of these observations was characteristic of juvenile rheumatoid arthritis, the investigators began to suspect that they were dealing with a previously unknown disease. Observation 3 led investigators to suspect that the disease was spread by some crawling insect, spider or tick. This last point is an interesting

deduction. Why do you think it was made by the investigators?

Question - Why did the investigators think that the disease was spread by a crawling insect, rather than a flying one?
Answer - The initial small bump suggested a bite. The appearance on the chest, abdomen or back indicated a bite by an organism that could crawl under the clothes. A flying insect would most likely bite on an exposed part of the body.

Obtaining the evidence to substantiate these suspicions was a more difficult matter. Several months later in subsequent interviews with infected people, one person remembered being bitten by a tick, which he had saved. The tick was identified as *Ixodes dammini*, a very small organism about the size of a pinhead.

How could further investigations be made to decide whether these ticks were the actual carriers of the disease?

The investigators set out traps on both sides of a river running near the infected area. Captured animals could be checked for the presence of ticks. Lyme and East Lyme, where a high incidence of the disease was found, were on one side of the river. Almost no cases had been reported from people living on the other side.

Prediction 1 - If *I. dammini* is found to be present in greater numbers in areas where the disease was found, then this would be a strong indication that the tick is linked to the presence of Lyme disease.
Result 1 - *I. dammini* was found to be 12 times more prevalent on the side of the river where Lyme and East Lyme were located. This result provided strong supporting evidence that the disease was carried and transmitted by the tick.

Question - Why did the investigators set out trips on both sides of the river?
Answer - Simply finding a high incidence of *I. dammini* on the same side of the river as the disease would not establish a relationship between the tick population and the disease incidence. It was important to find that when the tick population was low, the incidence of the disease was also low.
Question - Why were the two sides of the river an obvious location to examine for the presence of ticks?
Answer - The river provides a natural barrier that separates tick populations and prevents the movement of animals carrying the ticks. The presence of the river explains why the disease had not spread (at least not as seriously) to people on the other side and represented an obvious location to test the relation between tick presence and the disease.

1. Why would a higher population of ticks lead to a higher incidence of the disease? Why does the early observation that more people getting the disease lived near wooded areas seem logical knowing that the disease is probably spread by tick bites?

Although these observations were a strong indication that the tick carried the disease, far more positive proof would be provided if the bacterium or virus that caused the disease could be found in the ticks. Subsequent investigations found large numbers of an unusual, irregular-shaped bacterium in the digestive tract of the tick.

Is this the microorganism that causes Lyme disease? This question can be examined by extracting antibodies from the blood of people who have been infected by Lyme disease and by observing the reaction of the antibodies with the bacteria. If antibodies are present for the specific bacterium causing Lyme disease, they will combine with the bacteria, producing a reaction that can be easily observed. People who have been infected with a disease will normally generate antibodies to the infecting organism. These antibodies will confer some resistance to future infections. For example, people who have had chicken pox are resistant to another infection of chicken pox due to antibodies now present in their bodies.

What do you predict would be found in this test?
Prediction 2 - If the bacterium found in the digestive tract of the tick causes the disease, antibodies from previously infected people should react with this bacterium.
Result 2 - Subsequent observations showed that the predicted reaction did occur. Similar tests for antibodies to more than 200 known diseases carried by insects, ticks or spiders did not

indicate antibodies to any of these diseases.
Question - Why was the observation that antibodies from Lyme disease victims did not react with known disease organisms important?
Answer - This was strong evidence that Lyme disease was a new and previously unknown disease.

II. What would be found if antibodies from people who had not had Lyme disease were exposed to the bacteria from the ticks?

If a previously uninfected person were injected with the bacteria from the tick, what would you expect to happen?

These investigations gave strong support for the hypothesis that a new disease had been discovered and were helpful in determining the way this disease was spread and how it was caused. Lyme disease has since been found in a larger area of the northeast United States, the northern Midwest, and parts of the Northwest. Although it is a serious concern in these infected areas, the disease can be effectively treated with modern antibiotics if detected early.

REFERENCE
Habicht, G.S., Beck, G. & Benach, J.L. (1987). Lyme disease. *Scientific American*, July, pp. 78-83.

Case Study II
Photosynthesis & Oxygen Production
The investigation of photosynthesis using aquatic plants is one of the most common experiments performed in introductory biology laboratories. In these experiments *Elodea* is the plant most often used and the rate of photosynthesis is estimated by the amount of oxygen produced. Since *Elodea* is an aquatic plant, oxygen can be measured as the number of bubbles liberated into the water by the plant, or by collecting and measuring the total volume of gas produced.

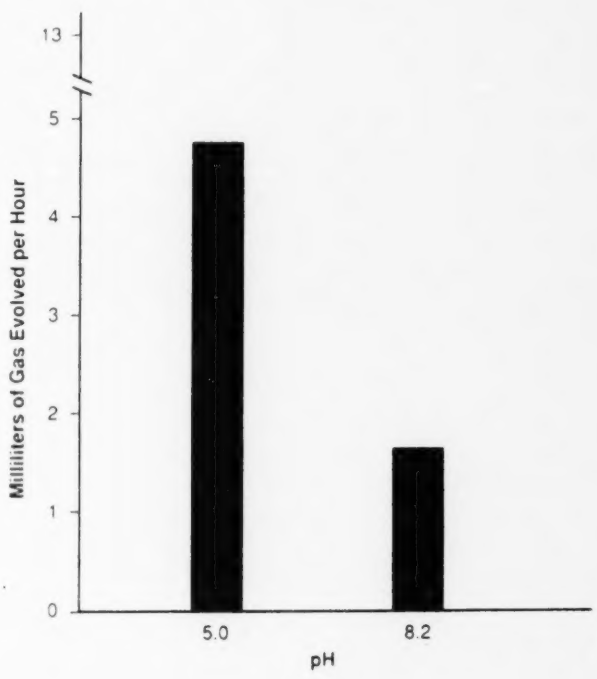
Using this experimental arrangement, the effects of several variables on photosynthesis can be investigated. The overall summary equation of photosynthesis:

Equation 1

$$6CO_2 + 6H_2O \xrightarrow{\text{Light Energy}} 6O_2 + C_6H_{12}O_6 \text{ (sugar)}$$

predicts that as the plant is exposed to more light and to increasing concentrations of CO_2, more O_2 and sugar will be produced. The effects of several other variables such as temperature, color of light and pH (acidity) of water bathing the plant have also been investigated. Especially interesting results have been obtained from experiments on pH effects, as shown in Figure 5.1 where a much greater volume of gas is produced at pH 5 than at pH 8. Why should this effect of pH be observed?

Figure 5.1. Gas production in *Elodea* at pH 5 and 8.2.



Several hypotheses could be proposed, but perhaps the most logical is the following:

Hypothesis—At acid pH levels (i.e. pH 5), CO_2 is at a greater concentration in the solution. This increased CO_2 results in a greater rate of photosynthesis as indicated by Equation 1.

This is a logical hypothesis because pH is known to affect the amount of CO_2 in the solution. Would you predict that low pH would increase or decrease CO_2 in the solution?

Prediction 1—Acid pH levels should *increase* the amount of CO_2 in the solution. The increased CO_2 would account for the greater rate of photosynthesis at pH 5.
Result 1—As shown in Table 1, the amount of CO_2 in the solution increases as the solution becomes more acidic. This result clearly supports the hypothesis.

Table 1

pH	Free CO_2 in Solution (grams CO_2/liter)
7	0.3
6	0.9
5	1.5

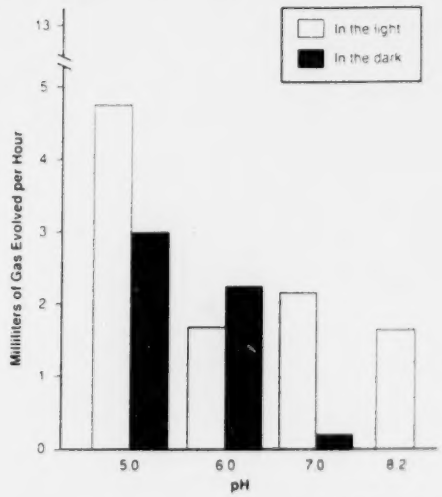
Question—What is another hypothesis that would explain the effects of pH?
Answer—Possibly the low pH increases the activity of enzymes involved in photosynthetic reactions so that the reactions proceed at a faster rate, increasing the rate of photosynthesis. This hypothesis is, however, much more difficult to test; it would require isolating the enzymes and investigating the effect of pH on reaction rate. Also, Result 1 provides strong apparent support of the original hypothesis.

> 1. What experimental conditions of pH and light should result in the greatest rate of photosynthesis? Is it possible that pH affects CO_2 concentration *and* has some other direct effect on the plant?

In another more detailed experiment, the amount of oxygen produced by *Elodea* was measured with the surrounding water pH at *several* different values between pH 5 and pH 8.2 under both light and dark conditions. The pH of the water bathing the *Elodea* was adjusted to the desired pH by adding sulfuric acid. The total amount of gas produced by the plant was collected and reported as milliliters of gas per hour. At each pH, measurements were made in constant light and in the dark. Considering Result 1, what results would you predict?

Prediction 2—Since more CO_2 is in the solution at acid pH values, more oxygen should be produced at pH 5 than at any of the more basic pH values. No oxygen should be produced in the dark at any of the pH values.
Result 2—As shown in Figure 5.2, more gas was produced at pH 5 than at more basic pH values. However, there was an entirely unexpected result; a considerable amount of gas was produced in the dark! Since no photosynthesis (and no oxygen production) can occur in the dark, how is this gas being produced?

Figure 5.2. Gas production in *Elodea* at several pH values in both light and dark conditions. The pH values indicate the pH of the water surrounding the *Elodea* plant.



An obvious question to ask at this point is: What is the gas being produced? Is the gas produced in the dark actually

oxygen or some other substance? These questions were investigated by analyzing the composition of the gas, and the results are shown in Table 2.

Table 2. Gas Composition.

	Treatment	% O_2	% CO_2	% N_2
Light	pH 8.2	47.3	1.4	36.3
	pH 6.0	21.8	40.9	18.5
Dark	pH 8.2	—	—	—
	pH 6.0	16.3	40.8	29.2

One immediate observation is that a large amount of CO_2 is produced in the light *and* dark at pH 6. At pH 8.2, however, very little CO_2 is produced. Instead, the largest component of the gas is O_2. Apparently some reaction is taking place at low (i.e. acid) pH values which produces CO_2, but this reaction does not occur at higher (i.e. basic) pH values. Therefore, experiments to investigate photosynthesis in *Elodea* by measuring oxygen production should be conducted at pH values near 8.

Question—If Result 1 clearly supported the hypothesis, why was a second experiment performed? Didn't the first experiment prove the hypothesis?
Answer—First, a hypothesis is never "proven" for sure. It is only supported by results that agree with predictions drawn from the hypothesis. Moreover, the greater the number of *different* predictions and results found that support the hypothesis, the greater our confidence that the hypothesis is "true" (but one can never be absolutely sure). Thus, the second experiment represented an attempt to increase confidence in the hypothesis. As it turned out, Result 2 revealed an unexpected effect that allowed a more complete understanding of *Elodea* physiology.

Question—What could account for the CO_2 production at low pH values?
Answer—One possibility is that a process or enzyme that produces CO_2 is much more active at low pH values than at high pH values. One such enzyme is carbonic anhydrase, an enzyme that catalyzes the conversion of carbonic acid (H_2CO_3) to CO_2 and water. Apparently, this enzyme is more active at low pH values.

> II. What was the control in the experiment that yielded the results in Figure 5.2?
> Why was the control especially informative in this experiment?
> Why is the gas production so high at pH 5 in the light in Figures 5.1 and 5.2?
> How would the results in Figure 5.2 be interpreted if no measurements had been made in the dark?

These investigations illustrate two very important points:
1. It is important to test a hypothesis with several predictions and experiments. As shown in Result 1, a single prediction and test can support the hypothesis, but further tests can reveal that support is not as strong as initially expected.
2. Experimental results can show effects that are unexpected and surprising, and these results can in turn lead to new and more informative investigations.

While these results do provide support for the hypothesis, other effects are revealed that indicate that the hypothesis cannot completely account for the observations. Additional experiments will be necessary to account for these unexpected results. Is the increased CO_2 production due to the action of carbonic anhydrase? Can the effects of carbonic anhydrase be separated from the photosynthetic response? The listed reference describes several possible investigations that address these questions.

In summary, strategies and materials do exist that can significantly assist both teachers and students. The exercises in this chapter should serve as examples of various kinds of effective exercises. Teachers can use these as a guide to writing their own exercises and/or as a source of material to use with their students. With relatively few key revisions in instructional organization and emphasis, teachers can have an immediate impact on student learning; with effective practice, students' abilities will consistently improve.

REFERENCES

Allen, R.D. (1990). *Critical thinking case study workbook: Biology.* Dubuque, IA: Wm. C. Brown Publishers.

Donovan, M.P & Allen, R.D. (1983). *Analytical problems in Biology.* Minneapolis, MN: Burgess Publishing Co.

Kosinski, R.J. & Stroup, D.J. (1987). A demonstration for your lab: *In vivo* carbonic anhydrase activity in *Elodea. The American Biology Teacher,* May, pp. 293-97.

Rau, A.D. (1991). Developing analytical reasoning and judgment skills in non-science majors. *Journal of College Science Teaching, 21*(2), 97-99.

Statkiewicz, W.R. & Allen, R.D. (1983). Practice exercises to develop critical thinking skills. *Journal of College Science Teaching, 12,* 262-266.

Tyser, R.W. & Cerbin, W.J. (1991). Critical thinking exercises for introductory biology courses. *Bioscience, 41*(1), 41-46.

Chapter Four

Getting Started

At first, implementing the teaching strategies and exercises discussed in previous chapters can be an awkward and uncomfortable process. What are the best strategies for introducing critical thinking to students? What kinds of comments can be expected from students? How should a teacher respond to these comments?

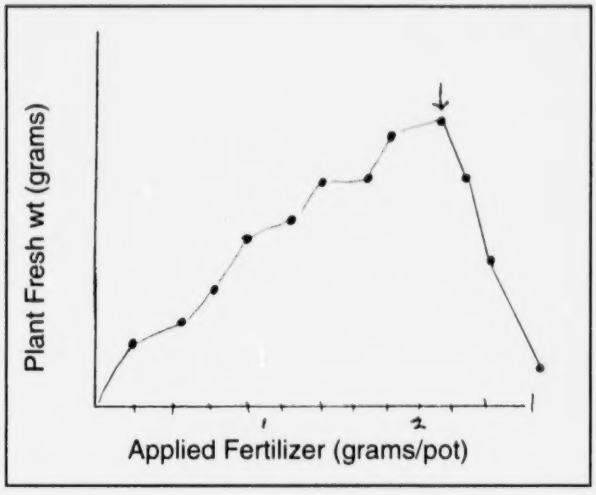
To address these concerns this chapter presents numerous introductory exercises, student responses and teacher strategies for dealing with these in laboratory, lecture and critical thinking exercises. The student responses discussed here represent, in our experience, the most common and in many cases, the most troublesome. If you can foresee and are prepared to deal with these, you will be far more effective at teaching critical thinking skills.

Laboratory

Perhaps the most obvious and immediate demonstrations of students' difficulty with the application of thinking skills are in their laboratory work. When required to test hypotheses, evaluate data, and propose interpretations in the laboratory, students are dealing with concrete personal activities and hands-on experience. Such activities will be the most "real" for students. Their misunderstandings are most obviously the result of thinking skill deficiencies and not confusion over information.

Because these deficiencies are so obvious, they can be addressed in a manner more meaningful to students.

As an example, consider an experiment where students investigate the effects of fertilizer concentration on plant growth. Suppose the students' hypothesize that fertilizer provides essential material for the synthesis of molecules by plants used in new plant growth. This hypothesis led to the prediction that plant growth increases as fertilizer concentration increases.



The data collected by these students is shown in the above graph.

In this experiment, the rapid decrease in plant growth after the point indicated by the arrow was unanticipated in the students' hypothesis and prediction. This observation is, however, an expected consequence of the applied fertilizer increasing the salt concentration in the soil and the resulting osmotic flow of water from the plant to the soil.

Several revealing student comments about these data might be made as indicated below and can offer you an excellent opportunity to address their misunderstandings. We have repeatedly observed these mistakes and have used them to effectively illustrate problems to students and to provide guidance and clarification.

STUDENT
"The experiment was bad; it didn't prove my hypothesis." (Students will often assume that they will get a lower grade if they don't "prove" their hypothesis even if the teacher assures them of the contrary.)

TEACHER
"First, proving the hypothesis is not the intent of an experiment. Testing the hypothesis is the purpose. Whether the results support or contradict the hypothesis makes no difference." The important thing is to conduct a well-designed experiment and make a sound interpretation. "The experiment will be equally informative in either case."

The teacher might also point out that unexpected or puzzling results can be very informative and can reveal insights into the events that are occurring under the experimental conditions.

STUDENT
"My results are wrong (or bad) because they didn't show what I expected."

TEACHER
Your results are neither wrong nor right but are the data you collected from your experiment. These data may be questionable because you suspect poor experimental technique or procedures. On the other hand, the data may show you something about the plants' response to fertilizer that you didn't expect.

Students will often ascribe unexpected results to "bad data" and do not realize that their observations (data) can reveal valuable information about their procedures or responses of the experimental organism.

STUDENT
"I'm not going to include the data at fertilizer concentrations higher than 2 grams per pot because these contradict the hypothesis."

TEACHER
"If you collected the data and have no other reasons to leave it out, then you must report and discuss them. Just because the results do not agree with what you expected would happen is no reason to disregard them. If you do, your experiment is seriously biased."

Students will often ignore or disregard results that contradict their preconceived notions and will emphasize only those results that "prove" what they expect. This is not a trivial problem and can lead to serious errors of judgment and interpretation.

STUDENT
"The data up to 2 grams/pot proves the hypothesis because plant growth increased as more fertilizer was added."

TEACHER
"Just because the data agree with the predicted results doesn't mean you have 'proven' the hypothesis. Maybe other, untested, hypotheses are also consistent with the results."

Students often expect that one experiment yielding results consistent with the prediction will "prove" the hypothesis. They see no need to further test the hypothesis since you already know that the hypothesis is "right." First, these students do not recognize that a hypothesis cannot be proven with certainty, and second, they have not realized that other hypotheses can be equally consistent with the data. For example, in this experiment it might be preposed that fertilizer stimulates photosynthesis or that fertilizer increases the uptake of water. While these may seem unfamiliar and unlikely ideas, they are possible interpretations of the results and could be considered as possibilities.

STUDENT LAB REPORT
A common problem with student lab reports is that their interpretation and discussion section merely repeats the results or observations. No effort is made to explain why the results appear as they do.

TEACHER
"The results section of your report gives your data (observations) but the discussion and interpretation section should give something very different—your explanation of your results. Your interpretations may sometimes seem speculative but should be a logical attempt at explanation."

Such mistakes illustrate students' failure to clearly distinguish observations and interpretations. This is an excellent opportunity for the teacher to emphasize the important differences that exist.

Classroom Interactions

Preparing a classroom situation to encourage analysis and critical thinking requires good planning, anticipation of student comments, and prepared teacher responses. The following examples illustrate several contrasting situations where thinking skills can be encouraged, or can actually be discouraged by inappropriate teaching.

These comparative situations are drawn from key differences identified by participants in numerous critical thinking workshops. After considering two presentations of a topic, one designed to develop thinking skills and the other a more traditional, information presentation, these participants identified the following differences as those most distinctive of thinking skill vs. traditional instruction as key differences identified by teachers. These should be especially useful to you when planning lessons.

As a context for these situations, consider the familiar example of organismal growth where the increase in the number of cells or organismal weight is shown by the data in the graph.

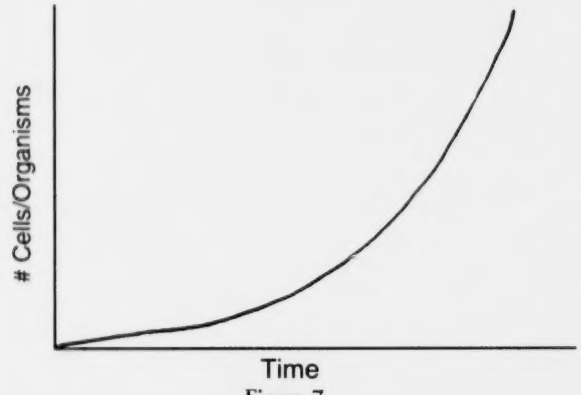


Figure 7

The way the concept is introduced can make an enormous difference to student understanding. Arnold Arons contrasts backwards science with forwards science (see Chapter 2). As he indicates, traditional instruction is often presented backwards to real science—conclusions and names are presented before the student has any basis for understanding material. In contrast, forwards science presents information with questions, observations and data first, followed by conclusions and names.

1. Backwards Science/Forward Science

a) Traditional approach (Backwards Science)

"The increase in the number of cells or organismal weight can be logarithmic as shown in the graph. The cell number or weight increases slowly at first and then increases more and more rapidly producing a 'J' shaped curve." This approach presents the name and definition first without giving students any basis for understanding why the curve appears as it does.

b) Thinking skills approach (Forwards Science)

"What happens when one cell divides? Two cells are produced. When these two divide, four cells are produced, then eight, then 16, then 64, and so on.

1 ⟶ 2 ⟶ 4 ⟶ 16 ⟶ 32 ⟶ 64

When these numbers are graphed, the curve appears as in Figure 7. This typical type of curve is termed logarithmic." Students are given a concrete illustration of why the graph appears as a "J" shaped curve and the name or term is given only after the concept is established.

2. Instructor as information source versus instructor as guide.

a) Information source

Teacher—"At three days on the graph, many more cells are being created than are dying."

(no student response encouraged or expected)

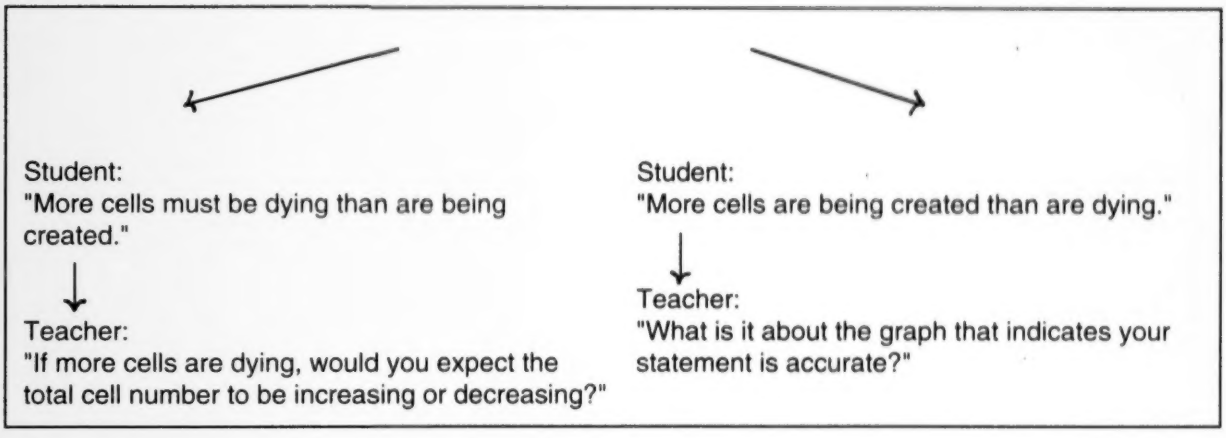
Or in an alternative interaction:

Teacher—"At three days on the graph, what can you say about the number of cells dying and those created?"

Student—"More cells must be dying than are created."

Teacher—"No, many more cells are created than are dying."

In the first instance, the teacher gives no opportunity for students to examine or interpret the data, but immediately provided the "answer" for them. In the second instance, even


Student:
"More cells must be dying than are being created."
Teacher:
"If more cells are dying, would you expect the total cell number to be increasing or decreasing?"
Student:
"More cells are being created than are dying."
Teacher:
"What is it about the graph that indicates your statement is accurate?"

though students have the opportunity to respond, the teacher's reply is a simple correction without leading students to correct and recognize their mistakes.

b) When the teacher acts as a guide, students are led to correct and justify their responses.

Teacher—"At three days on the graph, what can you say about the number of cells being created or those dying?"
Even with the correct student response, the teacher continues to seek a justification from the student so that the reason for the answer is established.

3. Assumptions identified and discussed
In traditional lectures, assumptions are rarely identified. Several assumptions are, however, inherent in Figure 7 if the data represent the theoretical cell numbers produced by: one cell — two cells — four cells — eight cells — 16 cells.

When these numbers are graphed, a "J"-shaped curve results, but this assumes there is no cell death and that generation time is constant. The teacher might ask:
"What assumptions are made about cell reproduction when Figure 7 is proposed as an accurate description of the increase in cell number?"
"Suppose these assumptions were not made, what would the curve look like?"
"How would you find out if the theoretical data were a good description of what really happens in cell reproduction?"

Identifying assumptions is one of the most difficult tasks for students, but even brief considerations during lecture will make major improvements in their skill.

4. Predictions
Extending beyond the available observations and results to make predictions is an excellent opportunity to examine student understanding and application. In the traditional approach, however, predictions are treated in a markedly different way than in a thinking skills approach.

a) Traditional approach
Teacher—"If the increase continues as shown in Figure 7, we would predict that the cells or organisms would exhaust the food supply and reach the limits of support by the environment. When this happens, the population may level off or decrease rapidly."

In this case, the teacher simply gives the predictions with little indication of how this relates to the available data.

b) Thinking skills approach
Teacher—"What would happen if growth continued as shown in Figure 7? From the trend you see, what would you predict would happen to the population?"

Student—"Growth should slow down and maybe cell number would become constant."

Teacher—"Why should growth slow down?" "Is a leveling off of cell number the only possible prediction?"

The teacher proposes questions and raises alternatives for students. It is more obvious that predictions extend beyond

the available data.

5. Instructor as presenter of information versus instructor as demonstrator of scientific procedure.

Fundamental procedures of analysis should be continuously demonstrated for students. In a traditional approach, however, with the teacher as presenter of information, such demonstration is rarely evident.

a) Presenter of Information
"When the number of cells is plotted against time as shown in Figure 7, the cell number is shown to increase more and more rapidly. This increasing growth rate shows that cells are being created much more rapidly than cells are dying. If this growth continues, less food and other resources in the environment will be available and growth will decrease."

In this case, the information is presented with no reference to operations in scientific procedure. Compare this to a presentation that draws attention to these operations.

b) Demonstrator of Scientific Procedure
"An observation that can be made from Figure 7 is that cell number increases more and more rapidly. One interpretation of these data is that cells are being created much more rapidly than cells are dying. If this growth continues and we assume there is a limited amount of food in the environment, then we can predict that growth will slow down."

Here the teacher utilizes observation, interpretation, assumption and prediction in the proper sense. Although no questions are indicated, there is ample opportunity even in these brief comments to present questions to students.

Most of the examples presented here rely heavily on questioning. It is important to bear in mind the advice in Chapter 2 that questioning need not be a time-consuming activity. More accurately, it represents a style of thinking through the material and illustrates the kinds of questions students should be asking themselves as they study and reflect on the information. If the teacher continuously asks him/herself questions about the material being studied, students should model this behavior as they study the coursework.

Classroom Checklist

A more detailed checklist of comparative characteristics identified by teachers who have been workshop participants can help assist teachers to evaluate instructional style. These are listed on the following pages and can be copied for use as a check sheet to assess your teaching as well as other teachers' performance. (See page 40.)

Several of these points of comparison may seem repetitious. They do, however, serve to illustrate finer distinctions between techniques and repeated observations of teaching styles in a variety of situations will make you much more aware of effective instruction.

Practice Exercises

Student success with practice exercises will depend on careful preparation on how to work exercises and on feedback about their initial efforts. As a general rule, you should start with fairly simple exercises and gradually increase the difficulty.

Several appropriate introductory exercises are presented in this section with typical student response. These initial exercises do not require biology concept application but focus on the basic activities of observation, interpretation, identifying assumptions and predictions. More difficult exercises, such as those in Chapter 3, can be introduced after students are experienced with the exercises.

Example 1

One day you meet a student watching a wasp drag a paralyzed grasshopper down a small hole in the ground. When asked what she is doing, she replies, "I'm watching that wasp store paralyzed grasshoppers to feed her offspring."

Which of the following additional observations would add the most strength to the student's reply?

1) Observing the wasp digging a similar hole.

2) Observing the wasp dragging more grasshoppers into the hole.
3) Observing the wasp sealing the entrance to the hole and concealing its location.
4) Digging into the hole and observing wasp eggs on the paralyzed grasshoppers.
5) Observing adult wasps emerging from the hole a month later.

Student Response 1:	Written Teacher Feedback:
1) No—digging another hole doesn't show <u>why</u> the hole is being dug.	Good.
2) Right answer—this shows that the wasp is using the grasshoppers for something.	What could grasshoppers be used for?
3) Wrong answer.	<u>Why</u> is answer wrong?
4) Wrong answer—the eggs may not hatch.	What if eggs <u>do</u> hatch? Would this affect your choice?
5) Wrong—the student probably wouldn't wait that long to see what happened.	Why would you assume this?

Such responses are typical of inexperienced students and illustrate answers that tend to miss the point as indicated by the teacher's written comments. The response to Choice 1 is a reasonably good argument against the choice, but other arguments leave much to be desired. In Choice 2, the student does not recognize that grasshoppers could be "used" for many purposes. Choice 3 has no argument at all and Choices 4 and 5 give reasons that are possibilities but do not address the question; these almost seem like excuses for eliminating the choice.

The teacher's comments on the paper need not be extensive; additional feedback can be given by brief discussion in class and posted answer keys:

Student Response 2:	Written Teacher Feedback:
1) Bad choice—digging the hole doesn't show <u>why</u> the hole is dug.	O.K.
2) Simply dragging more grasshoppers into the hole gives no reason for the grasshoppers being placed in the hole.	Good—other reasons possible.
3) Concealing the entrance could be done for many reasons other than feeding offspring.	
4) Best choice—shows some relation between young wasps and paralyzed grasshoppers.	Good—showing relation is essential.
5) Second best choice, but adult wasps could be coming from an underground nest not just because they hatched from eggs laid on grasshoppers.	O.K.—but why would grasshoppers be in the hole?

The quality and differences between the student responses should be obvious. Student 2 relates observations to possible interpretations and clearly recognizes that several interpretations may be possible for a given set of observations. Again, teacher comments can be brief.

Several other introductory exercises are given below. Try them with your students and give careful attention to their responses. These can provide you an excellent indication of their understanding and difficulties.

Example 2

Both of you wait until the wasp leaves the area, then you dig into the hole and observe three paralyzed grasshoppers, each with a white egg on its side. The student states that this evidence supports his reply in Question 1. Which of the following assumptions is he making?

1) The eggs are grasshopper eggs.
2) The wasp laid the eggs.
3) The wasp dug the hole.
4) The wasp will return with another grasshopper.
5) The wasp has left permanently.

Example 3

You take the white eggs and grasshoppers to the biology laboratory and are observed. If the student's comment in Question 1 is valid, which of the following would you predict?

1) The eggs are grasshopper eggs.
2) The wasp stung the grasshoppers.
3) The grasshoppers were dead, not paralyzed.
4) Immature wasps will hatch from the eggs.
5) The grasshoppers will recover from their paralysis.

Example 4

Two experimenters performed the same experiment. After a discussion they discovered that their conclusions did not agree. If you were asked to resolve their problem how would you best proceed?

1) Examine their experimental designs and their data.
2) Repeat the experiment yourself.
3) Have the experimenters repeat their experiments.
4) Examine the literature that reports the results of their experiment.
5) Ask an authority in that area what the answer is.

Example 5

Suppose as a result of your investigation in Question 4, you suspect that one of the experimenters was biased during the course of the experiment. If you accept the other experimenter's conclusion, which of the following assumptions did you make?

1) No conclusion should be accepted without evidence.
2) If the experiment is biased, his conclusion is not supported.
3) A conclusion produced by a biased experimenter may still be valid.
4) The unbiased experiment may have resulted in an unsupported conclusion.
5) The biased conclusion should be accepted.

Example 6

Some students added 1000 cells to a flask of nutrient medium and placed them in an incubator. The next day the flask contained 3000 cells. The students suggested the following interpretations.

a) Every cell divided at least once.
b) Some cells did not divide, but others divided more than once (i.e. some of the daughter cells produced by each of the original parent cells also divided).
c) Every cell divided more than once (i.e. all daughter cells also divided).

Which of the these would be acceptable interpretations?

1) a only
2) a and b only
3) b and c only
4) b only
5) a, b and c

Comparative Characteristics

Traditional Approach	Critical Thinking Approach
1. Students passive.	1. Students active.
2. Instructor makes all interpretations.	2. Students make some interpretations of experiments, graphs.
3. General questions or no questions.	3a. Specific questions. 3b. Teacher repeats questions. Student asks questions and instructor asks questions. Teacher repeats answers from students.
4. Data and analysis, if any, given by instructor.	4. Experiments used to illustrate concepts and main points. Students participate in analyses data.
5a. No student observations, instructor makes observations, if any. 5b. Assumptions or presence of assumption not discussed. 5c. Instructor makes conclusion.	5a. A question introduces each new topic or concept. 5b. Start a new topic by examining data and making observations. 5c. Look for and identify assumptions. 5d. Clearly identify observations as opposed to interpretations or assumptions. 5e. Look for ways to retest conclusions and interpretations.
6. Graphs and equations presented and explained by instructor.	6. Graphs and equations presented by instructor, students explain, make interpretations, predictions. Instructor acts as guide.
7. Instructor oriented.	7. Student oriented.
8. Instructor asks questions in any, students do not.	8. Question oriented discussion. New questions follow discussion.
9. Instructor gives the "answer."	9. Instructor asks specific questions,does not immediately "give the answer."
10. Real world examples. Relate to student experience.	10. Same.
11. Instructor is in front of class.	11. Instructor works "among" the students.
12. Instructor does not follow Thinking Skills Mode.	12. Instructor follows Higher Order Thinking Skills approach.
13. Instructor allots time for each concept.	13. This strategy could take a longer amount of time to present concepts and main points through experiments and scientific method. Instructor allots time for each concept.

Traditional Approach Continued

14. "Backwards science."
15. Instructor usually had detailed notes for all lecture concepts: "Terminology oriented."
16. Predictable-point to point presentation.
17. Theory presented first.

Critical Thinking Approach Continued

14. "Forwards science."
15. Instructors notes perhaps not as detailed. Textbook is reference.
16. Instructor acts as "guide" following detailed notes when necessary to save time.
17. Examples and observations lead to "Theory."

Several of these points of comparisons may seem repetitious. They do, however, serve to illustrate finer distinctions between techniques and repeated observations of teaching styles in a variety of situations to make you much more aware of effective instruction.

Chapter Five

Thinking Skills-What Do Standardized Tests Emphasize?

With the increase in emphasis and interest in thinking skills in biology, standardized tests and assessment instruments are placing greater focus on critical thinking. Considerable attention is given to designing test items to evaluate students' skills in analyzing experimental data, interpreting results, identifying assumptions and the other skills comprising critical thinking. Clearly, success on these tests requires more than content knowledge and recall—critical thinking skills are essential. Attempts to prepare for the tests by simply covering more content in greater "depth" will be insufficient preparation. Students with little instruction and practice using critical thinking skills will likely find these tests exceptionally difficult and frustrating. If, however, appropriate instruction is provided as described in the previous chapters, students will make major improvements in their performance.

The sections in this chapter describe the intent of the questions on standardized tests, provide examples from the tests and indicate how these items assess critical thinking skills. These items provide excellent examples of what is expected of students and additional guides to the teacher for thinking skill exercises. Although shown in a multiple-choice format, all the sample items can be used as excellent written justification exercises, as described in Chapter 3.

I. American College Testing (ACT) Program Science Reasoning Test

According to ACT this test is:

"Designed to measure students' abilities and skills in scientific reasoning—not their prior knowledge of information treated in the stimulus [test item]."

...."Advanced knowledge in these subjects is not required, but background knowledge at the level of a high school general science course may be required to answer some questions."

Indeed all testing in biology and other sciences on the ACT test is encompassed by the science reasoning test. In other words, no testing is devoted solely to recall of knowledge in biology.

The following two samples are taken from previous ACT tests and are representative items. Each sample provides experimental data followed by a series of questions requiring the application of reasoning skills.

SAMPLE 1:

The immune system provides a defense against foreign materials (antigens, usually proteins) that enter the mammalian body. Lymphocytes are an important part of this defense system that have differentiated into B cells and T cells. Most B cells are found in the spleen, but they are also found elsewhere in the body. B cells function in the production of antibodies. These antibodies combine with antigens to form an antibody-antigen complex. T cells, which are amoeba-like, migrate throughout the body but congregate especially in lymph nodes and the spleen. These cells engulf and destroy antibody-antigen aggregations. They also attack viruses, bacteria and transplanted tissues.

The following experiments were designed to study the effect of the thymus gland on the development of the immune system in mice:

Experiment 1

The thymus was removed (a thymectomy) from both newborn and adult mice. The newborn mice never produced functional T cells; antibodies were produced, but only against certain antigens. When foreign tissue was transplanted into the newborn thymectomized mice, they did not reject the tissue. However, the mice thymectomized as adults continued to produce functional T cells, to produce antibodies against all antigens and to reject transplanted tissue.

Experiment 2

Cells were removed from the thymuses of 10-day-old and 12-day-old mice. The cells were then grown in a tissue culture plate. T cells did not develop in cultures of the 10-day-old thymus, but did develop in cultures of the 12-day-old thymus.

Experiment 3

The thymuses of newborn mice were tagged with a radioactive material. They were then transplanted into other nonirradiated newborn mice whose thymuses had been removed. Within five days, most of the radioactive material was located in the lymph nodes and spleens of the

nonirradiated mice. Most areas in the transplanted thymuses now contained new populations of normal, but nonradioactive, cells.

The following questions should be answered based on the experimental evidence in Sample I:

1. A thymectomy would most influence the immune system development of:

A. A newborn mouse.
B. A 14-day-old mouse.
C. An adolescent mouse.
D. An adult mouse.

[Interpretation of data] The student must interpret the statements in Experiment 1 and generalize to the conclusion in Item 1–immune system development of a newborn mouse is most influenced by a thymectomy (Choice A).

2. Which of the following results would be expected if an accident destroyed the thymus of an adult mouse?

A. The mouse would no longer be able to fight off infections.
B. The mouse would be unable to reject transplanted tissue.
C. The mouse would continue to exhibit normal immune responses.
D. Antibodies would no longer be produced by the mouse.

[Making predictions from experimental data] Since removal of an adult mouse thymus did not appear to affect the immune response as shown in Experiment 1, then destruction of the thymus should have the same result (Choice C).

3. When reporting the data obtained in Experiment 3, the experimenter is assuming that the function of the thymus was NOT affected by:

I. Transplantation.
II. Being tagged with radiation.
III. The age of the mouse receiving the trans plant.

A. III only.
B. I and II only.
C. II and III only.
D. I, II and III.

[Identification of assumptions] The student must recognize that if transplantation or irradiation did have an effect, then the effect of the thymectomy on immune system development could not be investigated because the radiation and/or transplantation could be the cause of any observed effects. Thus the experimenter must assume (i.e. accept with no supporting evidence) Choice B.

SAMPLE 2:

A series of experiments was performed to study the environmental factors affecting the germination of *Petalostemon villosum.*

Experiment 1

When the outer coverings protecting the seeds were removed, seed coats of two different colors were observed—dark brown and light brown. Seeds of both colors were cut in half and tested with tetrazolium chloride. (Positive tetrazolium chloride [TZC] tests indicate that metabolic processes are occurring and that the seed is therefore capable of germinating.) Out of 20 light brown seeds tested, 16 were positive for TZC, whereas only two out of 20 dark brown seeds were positive.

Experiment 2

Whenever possible, light brown seeds were selected for this experiment. Seeds were divided randomly into six groups of 25 seeds each. The outer coverings were left on two groups of seeds. With two other groups, the outer coverings were removed, and the seed coats were left undamaged. Finally, with the last two groups, the outer coverings were removed, and the seed coats were scarified (scratched). Each group of seeds was then placed in a petri dish containing two pieces of filter paper over a 2 cm layer of sterilized sand. A piece of filter paper was placed on top of the seeds, and water was added until the sand and paper were saturated. The test conditions under which the dishes were placed and the results obtained are given in the following table:

Seed preparation	# of hours of light per day at 20° C	Total number of seeds germinated at: 24 hrs	48 hrs	96 hrs	7 days
Outer coverings	24	0	0	0	0
kept intact	0	0	0	0	0
Outer coverings removed- seed coat kept	24	0	2	4	9
intact	0	0	1	3	7
Outer coverings removed- seed coat	24	18	22	23	23
scarified	0	19	24	25	25

The following four questions should be answered based on the experimental evidence in Sample 2:

1. Petalostemon villosum grows in areas where blowing sand dunes are found. On the basis of this information and the results of the experiments, which of the following conclusions about the germination of these plants in the wild appears most valid?

A. The seeds germinate as soon as they drop off the parent plant.
B. Blowing sand can absorb water faster than the seeds can, which prevents any of the seeds from germinating.
C. Blowing sand rubs the outer coverings off the seeds and scarifies their seed coats.
D. Blowing sand provides the seeds with a constant amount of moisture, which causes them to germinate at a faster rate.

[Drawing conclusions from data] The data clearly show that seeds with scarified seed coats exhibit higher germination. The blowing sand would enhance germination by rubbing off the covering and scarifing the seed coat. The student must relate information in the data (scarification enhances germination) to the role of the blowing sand (Choice C).

2. It was assumed in the design of Experiment 2 that all of the seeds were:

A. Dark brown.
B. Capable of germinating.
C. Impermeable to water.
D. Scarified.

[Identification of assumptions] The student must recognize that if all the seeds were not capable of germinating, then valid interpretations could not be made since seeds may not have germinated due to causes other than the treatments given (Choice B).

3. On the basis of the results of the experiments, which of the following conclusions about the two scarified seeds that did not germinate in Experiment 2 is the most likely to be valid?

A. They would have germinated if they had been placed under 24 hours of darkness per day.
B. Their seed coats must not have been scarified properly.
C. They were dead prior to the beginning of the experiment.
D. They would have germinated if the experiment had continued for a longer time.

[Drawing conclusions from data] Examination of the data by the student should show that many seeds germinate even when the seed coat is not scarified and that 48 of 50 seeds did germinate. Thus conditions were highly favorable for germination unless the seeds were dead (Choice C).

4. Suppose dark-colored seeds were tested using the same

procedures as those used in Experiment 2. How many out of the 25 seeds whose outer coverings were removed and the seed coats scarified would probably germinate?

A. 0
B. 2 to 3
C. 5 to 6
D. 16 to 17

[Making predictions] Experiment 1 indicated that 10 percent of the dark-colored seeds were capable of germinating. From these data the student should predict that 2 to 3 (about 10 percent) of the 25 tested seed should germinate.

The questions on this test are highly specialized in terms of specific content. It is highly unlikely that students will have prior knowledge of the immune system experiments or the effects of scarification on seed germination. If students know, however, the basic principles of animal physiology and of seed structure and germination, they should be able to analyze these experiments and apply thinking skills to solve these exercises.

II. National Association of Biology Teachers Test

In 1988, NABT assembled a test that biology teachers could use to evaluate their students' understanding of basic biological concepts and ability to apply these concepts. The following questions were taken from this test and illustrate how various aspects of thinking skills are addressed.

1. A cell biologist hypothesized that the nucleus of a cell is necessary for cell life. She removed nuclei from a number of cells, compared them to a control group of cells with nuclei, and collected the following data:

	Number of Cells Still Alive	
Days After Removing Nucleus	Without Nucleus	With Nucleus
1	81	79
2	62	78
3	20	77
4	0	74
15		67
30		65

Based on those data, the biologist would reasonably conclude that a cell:

A. Cannot live without a nucleus.
B. Needs a nucleus to survive more than a few days.
C. Cannot divide without a nucleus.
D. Needs a nucleus to reproduce.
E. Can live only one day without a nucleus.

[Drawing conclusions from data] The student must evaluate the hypothesis in relation to the data that show cells can live as long as three days without a nucleus but not as long as four days. Thus, data examination should lead the student to Choice B.

2. A reporter wrote, "We are lucky that heart disease is not a genetically dominant disorder, or everyone would have it by now." The report has made an error by assuming that:

A. Heart disease is a major cause of death in the U.S.A.
B. Recessive traits are always weak.
C. Human populations follow the laws of heredity.
D. Dominant genes eventually become the most frequent genes in a population.
E. Heart disease might be inherited as a single-gene disorder.

[Identification of assumptions] The student must recognize that the reporter thinks dominant genes increase in gene frequency and must be making this assumption (Choice D) as a basis for the statement.

3. A student places six seedlings into each of four glass containers. Each container is covered with a different color of cellophane, so that only one color of visible light can pass through: A = yellow; B = red; C = green; and D = clear (all colors of light). Each is given the same amount of water and placed in sunlight for the same period of time. In which container(s) would you expect the least growth to occur?

A. A
B. B
C. C
D. D
E. B & D

[Making predictions] The student is required to know that green light is least effective in carrying out photo-

synthesis. From the description of the experiment, the student should recognize that seedlings in Container C would be receiving only green light, and should predict that seedlings in Container C will exhibit the least growth.

4. Viruses do not contain ribosomes. Therefore, viruses:

A. Depend on a host organism to produce their protein.
B. Do not contain genetic material.
C. Are incapable of using proteins.
D. Substitute carbohydrates for proteins.
E. Do not contain protein.

[Applying concepts to evaluate conclusions] The student must know that ribosomes are necessary for proteins to be synthesized from the information in mRNA. The student must then apply this knowledge to conclude that the virus must utilize ribosomes from another source (the host organism).

It might be argued that at least some of these questions could be answered by just recalling the "right answer." For example, in Question 4 the student could remember that viruses utilize ribosomes in the host cell. However, if the student is also capable of using the logic outlined with Question 4, a more powerful and successful approach is available to reason to an answer or to check and validate memory.

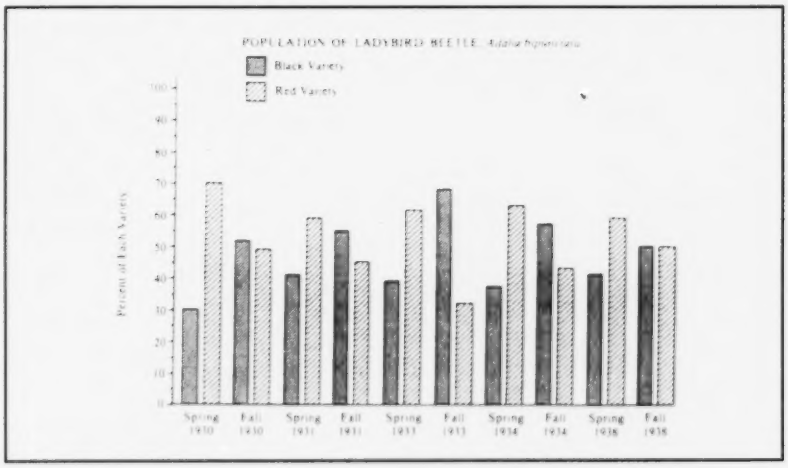
III. The Educational Test Service Advance Placement Biology Examination

Advanced placement biology offers the opportunity for high school students to pursue college-level studies. To obtain college credit, students completing the course must pass an advanced placement examination administered by the Educational Testing Services.

As described by the Educational Testing Service:
"The multiple-choice section (of the examination) is designed to test the student's ability to recall, understand and apply the wide range of ideas and concepts of biology."

The following examples were taken from the examination and indicate how thinking skills must be applied.

SAMPLE 1:
The figure below refers to the following question:



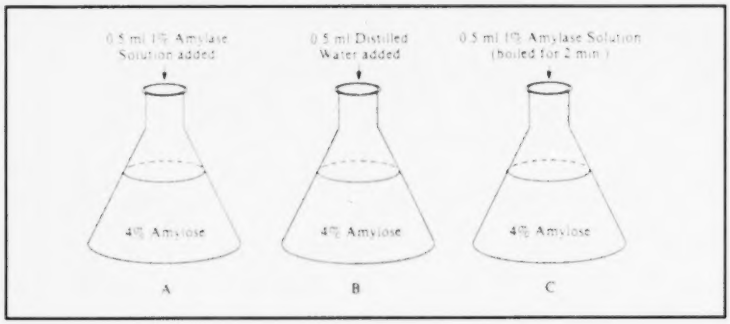
1. The most likely conclusion from the information in the graph is that:

A. Ladybird beetles mate in the fall, but the eggs do not hatch until the following spring.
B. Two different species are involved.
C. There are more red beetles in the fall than in the spring of each year.
D. The allele for red color is co-dominant with the allele for black.
E. One variety may be adaptively superior at one time and the other at another time.

[Drawing conclusions from data] The student must examine the data in the graph and recognize that in the fall the black variety predominates, while in the spring the red variety predominates. This information must be evaluated relative to each choice. The one possible explanation or interpretation of the data is Choice E.

SAMPLE 2:

A biologist prepares an *in vitro* analysis of the activity of the enzyme amylase, which promotes the hydrolysis of polysaccharides to monosaccharide residues. Three flasks containing 5 milliliters of 4 percent amylase (starch) in water are prepared with the addition at time zero of each of the substances indicated in the diagrams below:



1. In an experiment to test the effect of amylase on starch, the control would be:

A. Flask A only
B. Flask B only
C. Flask C only
D. Flasks A and B
E. Flasks A and C.

[Analysis and evaluation of experimental design] The student must examine the function of each flask and treatment. From this analysis the student should recognize that the only variable between Flasks A and B is the addition of amylase. Since no amylase is added to Flask B (i.e. this flask controls for the effects of any variables other than the presence of amylase), this flask would be the control (Flask B).

2. After two minutes a positive test for sugar would most likely be observed in:

A. Flask A only
B. Flask B only
C. Flask C only
D. Flasks A and C
E. Flasks B and C.

[Prediction of experimental results] No catalytic breakdown of starch should occur in Flasks B or C. In B no enzyme was added and in C the amylase should be denatured by boiling. In Flask A, however, the amylase should act on the starch to produce sugar. The student would be expected to carry out this analysis of the experiment (Choice A).

3. Support for the hypothesis of enzyme denaturation can be obtained by comparing starch digestion in:

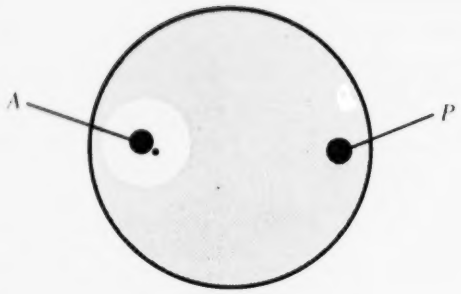
A. Flasks A and B after 5 minutes
B. Flasks B and C after 5 minutes
C. Flasks A and C after 5 minutes
D. Flask A at time zero and again after 5 minutes
E. Flask B at time zero and again after 5 minutes.

[Prediction of experimental results and evaluation of evidence supporting hypothesis] The student must recognize that the variable between Flasks A and C is the treatment of the amylase. If boiling denatures enzymes and if denatured enzymes cannot catalyze a reaction, then no starch digestion should be apparent in Flask C. Comparison of Flasks A and C, then, would permit an evaluation of the enzyme denaturation hypothesis.

A and C–A will show significant sugar present (enzyme active) while C will show little or no sugar (boiled enzyme is denatured and inactive). The only difference between the two flasks is that in C the enzyme has been denatured.

SAMPLE 3

A sterile agar plate, I, is streaked with a pure culture of bacteria by means of aseptic techniques. Paper discs treated with the antibiotics Aureomycin (A) and penicillin (P) are placed at opposite sides of the plate, as shown in the diagram above. The plate is examined after a 24-hour incubation period, and a clear ring is discovered around Disc A, but not around Disc P. Within the clear ring around Disc A, a single bacterial colony with physical characteristics like those of the pure culture is observed. A second sterile agar plate, II, is then streaked with



this single colony and also incubated with antibiotics.

1. The single colony found within the clear ring in plate I is most likely made up of the descendants of a bacterial cell that:

A. contaminated the agar plate
B. contained information conferring resistance to Aureomycin
C. changed its response to Aureomycin as a result of being exposed to the antibiotic
D. was susceptible to both penicillin and Aureomycin
E. emigrated from another area of the agar plate.

[Interpretation of experimental results] The student must recall that mutations arise by chance and are not induced. From this, it can be concluded that the surviving colony in A must have had preexisting information conferring resistance (Choice B)

2. Which of the following would most likely be observed in plate II after 24 hours?

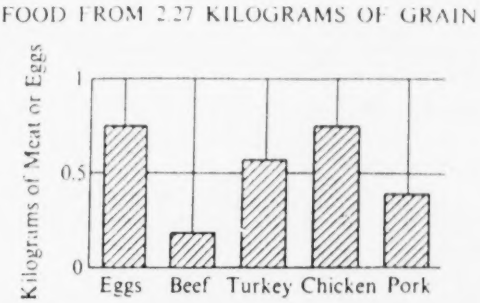
A. A clear ring larger than that around Disc A in plate I would appear around disc A only.
B. A clear ring larger than that around Disc A in plate I would appear around Disc P only.
C. A clear ring would be a clear ring around both Disc A and Disc P.
D. There would be a clear ring around both Disc A and Disc P.
E. There would not be a clear ring around either Disc A or Disc P.

[Prediction of experimental results] If the bacteria from the colony in A is used to form plate II, these bacteria will be resistant to Aureomycin and no clear ring will be formed at A—thus eliminating Choices A and D. Since these bacteria were obtained from a colony resistant to penicillin, no clear ring should appear around A or P (Choice E). The student is required to analyze the problem in this way to complete the exercise.

To solve these problems on the AP biology test, students must be able to practice the indicated thinking skills. Memory alone will not allow significant success with these exercises.

IV. The NTE (National Teachers Examination) Biology and General Science Specialty Area Test.

The NTE test is prepared by the Educational Testing Service and is intended to "...measure in an objective and standardized manner academic knowledge and skills important for beginning teachers and other educational professions." Contrary to the other tests that are prepared to test students, this test is aimed at teachers. In this case also, critical thinking skills are evaluated.



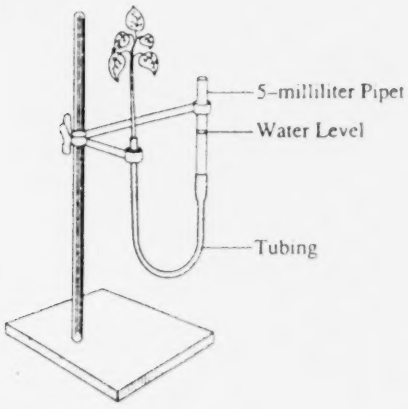
SAMPLE 1:

The graph above illustrates the number of kilograms of meat or eggs produced for every 2.26 kilograms of grain eaten by an animal. Which of the following changes in the eating habits of people in the developed world would result in the most efficient use of grain?

A. Eating more pork than eggs
B. Eating more chicken than beef
C. Eating more beef than eggs
D. Eating more turkey than chicken
E. Eating more eggs than chicken

[Drawing conclusions from experimental evidence] From the graph it should be recognized that more eggs and chicken can be produced per unit of grain (i.e. result in the

most efficient use of grain). From this it can be concluded that Choice B is best.



SAMPLE 2:
The stem of a plant shoot was held beneath water and cut diagonally. Tubing attached at one end to a pipette was filled with water and the tubing forced over the cut end of the shoot while still immersed in the water. The tubing and pipette were clamped as shown in the diagram above. Measurements were taken by reading the water level in the pipette every 15 minutes.

1. The experimental setup is designed to measure:
   A. Root pressure
   B. Photosynthesis
   C. Transpiration
   D. Guttation
   E. Translocation.

   [Analysis of experimental design] It must be recognized that the experimental setup will measure the loss of water from the plant shoot and will thus measure transpiration (Choice C). This question relies most heavily on memory, but the following two require considerably more analysis.

2. Which of the following would have the LEAST effect on changing the water level from its initial value?
   A. Ambient temperature
   B. Number of leaves
   C. Humidity
   D. Dissolved CO_2 in the water
   E. Number of open stomata.

   [Prediction of experimental results] The factors that affect must be analyzed in terms of how each would have an effect. All would have at least some effect except choice D.

3. Which of the following actions is most likely to lead to the most rapid lowering of the water level in the pipette?
   A. Increasing the light intensity
   B. Sprinkling the leaves with water
   C. Covering the plant with a clear plastic bag
   D. Covering the leaves with petroleum jelly
   E. Covering the plant with a green plastic bag.

   [Prediction of experimental results] As in Question 2, analysis of the factors affecting transpiration should lead the student to recognize the light will result in stomates opening and thus greater transpiration (Choice A).

SAMPLE 3:
This example is somewhat different from the others because it assesses the teacher's ability to evaluate student responses in relation to an accurate analysis of the experiment. As such, it can be regarded as even more difficult since it requires an analysis of an evaluation.

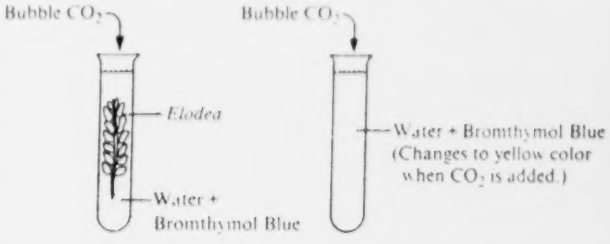


Figure 1 - Experimental Figure 2 - Control

A biology teacher sets up an experiment as indicated in the diagrams above. A sprig of *Elodea*, water and bromthymol blue indicator are placed in a test tube. Carbon dioxide is bubbled through the solution for a few minutes, which

changes the color from blue to yellow. The plant is allowed to photosynthesize. During the day, the yellow solution turns blue; at night, it turns back to yellow. The control for this demonstration is a test tube of water and bromthymol blue, which turns yellow when carbon dioxide is bubbled through the solution.

The students are asked to explain what caused the color changes observed in the experimental tube shown in Figure 1. Five students respond as follows:

Student A:	Bromthymol blue turns yellow in an acid medium and blue in a basic medium.
Student B:	Photosynthesis uses up carbon dioxide, causing the solution to turn yellow, and cellular respiration causes the solution to turn blue.
Student C:	Carbon dioxide, water, sunlight and chlorophyll are all necessary for photosynthesis.
Student D:	Oxygen is released during photosynthesis, which causes the solution to turn blue, then yellow at night.
Student E:	During the day, photosynthesis uses CO_2 and causes the yellow color to change to blue; at night, the release of CO_2 by cellular respiration causes the blue color to change to yellow.

1. Which student understands the requirements of photosynthesis, but has not answered the question?

[Evaluation of interpretations] Student C correctly lists the requirements for photosynthesis but in no way uses this information to explain the color changes or relate the events of photosynthesis.

2. Which student best answers the question?

[Evaluation of interpretations] Student E relates the utilization or release of CO_2 to photosynthesis and respiration and, in turn, to the color change.

3. Which student best understands the chemical reasons for the color change, but did not answer the question?

[Evaluation of interpretations] Student A explains the relation between pH and color change but does not relate this to the events of photosynthesis and respiration of *Elodea* in the experimental test tube.

These NTE questions obviously require much content knowledge and recall of information on biology. Also required is the ability to apply this information through analysis, evaluation and interpretation. Attempting to utilize one without the other will not lead to success. Teaching students one without the other will not lead to success.

SUMMARY

Standardized tests clearly assess students' thinking skills. Practice with critical thinking questions will significantly improve students' skill and their scores on such tests.

These example exercises, and others that can be obtained from the testing agencies, are excellent practice exercises. For effective practice, however, students should write their justifications for acceptance or rejection of each choice and have these justifications evaluated by you, the teacher.

Chapter Six

Student & Instructor Difficulties

At several points in the preceding chapters, the difficulties with critical thinking instruction exhibited by students and teachers have been discussed. This chapter serves to re-emphasize and summarize these difficulties. A second intent is to provide additional examples of practice exercises that further illustrate student misconceptions and difficulties.

In order to improve thinking skills, an instructor must provide students with multiple opportunities to make good decisions. The instructional strategy outlined in the previous chapters provides the necessary instructional methods to significantly improve student thinking skills. However, as with any method of thinking skills instruction difficulties for both the student and the instructor will occur. In order to foster thinking skills instruction, you need to be aware of these difficulties and you need to be able to incorporate methodologies in your teaching that will allow you to solve the problems that result.

Decision making is a complex, multi-stage process involving assumptions, diverse analytical approaches, qualitative judgments and incomplete evidence. When engaging in this process, people exhibit a variety of tendencies and difficulties which limit their ability to make rational, sound decisions.

When evaluating thinking skills, emphasis is placed on recognizing and developing an awareness of the difficulties, analyzing the way an individual's decision-making process operates, and organizing the process for greater effectiveness.

The teacher should be the role model of a rational, logical person practicing critical thinking. Whether your instruction relies on a traditional lecture format or more on class discussion, as a teacher you must provide the model for your students to follow. In any procedure, however, students should be challenged with thought-provoking questions. The following section describes the development and evaluation of written exercises. These same guidelines and the resulting exercises, however, serve as excellent lecture or laboratory questions.

One of the most important points we wish to make in this book is that critical thinking skills in science must be developed within the context of science instruction. This places a considerable burden on the science teacher to design, adapt and manage instruction in the science class so that students learn to think critically as well as learn the necessary concepts and information. Even with the examples and models described in the previous sections, teachers will face difficulties when attempting to include instruction on critical thinking in their classes. To do so will require a good appreciation of the processes of science and well-defined instructional procedures to avoid and overcome student difficulties. In your class never say, "Now we will begin a new section on critical thinking."

One problem with thinking skills instruction that both students and instructors share is based on an understanding of "proving" in terms of providing increased confidence. What does it mean to "prove" a fact or an interpretation? The sometimes overwhelming desire for certainty will frequently lead students to view proof and fact in absolute terms. Indeed, the very word, "fact," connotes certainty and indicates a truth that is beyond doubt and needs no further proof.

Innumerable arguments between teacher and student have been generated by the student discovery of a fact in a textbook that contradicts the correct answer to an exam question. We have found that students are generally unimpressed with arguments that their fact is a special case or is not universally accepted. In their view, isn't a fact a fact? Once a fact is "proven," how can its truth be questioned? We will never forget one student who questioned the need to further test a hypothesis. After discussing an experiment that clearly supported their hypothesis, we asked, "What other experiment could we do which would test this hypothesis?" His immediate response was, "Why do we need to test it again? Didn't this experiment "prove" the hypothesis?"

Such views are indicative of severe and persistent student misunderstandings regarding the meaning of fact and proof in scientific investigation. In good scientific procedure, evidence accumulated in support of a hypothesis increases our confidence that the hypothesis is true, but does not "prove" the hypothesis in any final sense. In this view, a fact is a well-supported hypothesis, one in which we can have a very high degree of confidence. As discussed previously, this tentativeness of science, without any absolute certainties, is disconcert-

ing to students who want to be sure their knowledge is correct.

In more traditional science instruction, with an emphasis on factual recall, students are seldom, if ever, required to analyze data, make relativistic arguments, or provide a rational line of reasoning. Students (and teachers) thus avoid coming to grips with evaluating the strength of evidence and support for a fact.

When students with such a traditional background are faced with evaluating evidence and establishing proof, they frequently ignore good scientific procedure and are strongly influenced by pre-conceived notions of what they think is right. Proof is sometimes seen where none exists, contradictory evidence is ignored or dismissed as being "wrong," and students are led to attribute a high degree of certainty in inappropriate situations. Good instructional design fosters good science, and student gains exceed the instructional risks.

One aspect of an appropriate teaching strategy is the use of multiple-choice problems as discussed in Chapters 2 and 3. Many teachers argue for the superiority of open-ended essay questions, since these "allow the students to show what they know." Often, however, student responses to such questions can be vague and tend to relate extensive but general information about the topic without answering the question in specific terms.

On the other hand, multiple-choice questions can be constructed with choices that force students to employ more subtle reasoning and can, thus, provide more sophisticated practice (Stroup 1992). Moreover, different choices can require students to examine different points of view on a problem. Students will often fail to do this on an open-ended problem. An additional benefit is that choices can focus on several common misconceptions that students may have about a concept or concept application. Thus, if properly constructed, multiple-choice questions allow the teacher to direct student learning and practice in ways not possible with other kinds of exercises. You may discover that your students have had little formal practice at making good decisions.

If students were simply asked to pick a choice, multiple-choice problems would have little, if any, of the potential benefits. If used properly, students are required to write out a full justification for accepting or rejecting each choice. The importance of a complete justification for both the rejected choices as well as the most acceptable choice cannot be emphasized too strongly. If students are to derive maximum benefit from a problem, they must practice and learn to logically reject misleading statements. And the time spent on the process of writing, evaluating, and rewriting their justifications as an out-of-class exercise permits students to spend the time necessary to reflect on and refine their justifications. Several additional examples are provided here to illustrate the use of these exercises and some difficulties that should be considered when incorporating thinking skills instruction into your classes. Begin your instruction by using simple exercises as discussed in Chapter 4, and then progress to more difficult problems as the students gain some experience and confidence. The example exercises that follow show varying degrees of difficulty (simple example to complex example) and illustrate acceptable and unacceptable justifications. Keep in mind that, with practice, you will receive what you expect from your students.

Example Number 1

Circle the correct answer. Justify in writing one choice as best and likewise justify your rejection of all other choices.

A student is using a compound microscope with parfocal lenses. Figure A represents the total field of view of this field-centered microscope with the 10X objective in place. If this student changes to a 43X objective, he will most likely see:

1. The same letters, size of the letters unchanged
2. The same letters, size of the letters reduced and all letters centered
3. The same letters, size of the letters enlarged and all letters centered
4. The letter B, enlarged
5. The letter C, enlarged.

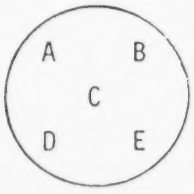


Figure A

ACCEPTABLE STUDENT ANALYSIS:

1. Increasing the magnification decreases the size of the field. You would not expect to see the same letters, size unchanged. **Reject.**
2. Changing to the 43X objective would decrease the total field of view. You would therefore only see a small portion of the original 10X field of view. You would not expect to see the same letters reduced in size and centered. **Reject.**
3. Increasing the magnification would decrease the size of the field of view. You would expect a letter or letters to be enlarged, however you would not expect to see the same letters enlarged and centered. **Reject.**
4. The microscope centers on the field of view when objectives are changed. You would not expect to see the letter B enlarged because of the original position of B in the field of view. **Reject.**
5. **Best choice.** See #1 and #4 above. Since the field-centered microscope has parfocal lenses and the total field of view decreases as the magnification increases, you would most likely expect to see the letter C enlarged.

This is an exercise with a low degree of difficulty that could be used after a laboratory on microscopy. This is often the first laboratory in many laboratory manuals.

Example Number 2

A scientist plans to use a microtome to cut sections of tissue so thin that a typical cell will be cut into about 20 sections. Staining the sections with a dye will allow the scientist to make careful observations of internal cell structures. Which of the following procedures would give the most complete picture of the internal structures of a cell?

Circle the correct answer. Justify in writing one choice as best and likewise justify your rejection of all other choices.

1. Look at one section.
2. Look at 20 sections from 20 different pieces of tissue.
3. Stain all of the sections, then look at 20 sections from 20 different pieces of tissue.
4. Look at 20 consecutive stained sections of a cell from the same piece of tissue.
5. Either #2 or #3 would be a good procedure to insure observation of the complete internal contents of a cell.

ACCEPTABLE STUDENT ANALYSIS:

1. Looking at one section will only show part of the cell, and all of the internal structures of that cell are most probably not in that section, so it will not fully show the contents of the cell. Also, the sections are not stained so it will not even be possible to observe the internal cell structures. **Reject.**
2. Observing 20 sections from 20 different pieces of tissue may not provide a complete picture of the internal structures of a cell, because some of the sections may be identical while others are left out, thus not showing all of the internal structures. As in #1, the sections are not stained so the internal structures cannot be seen. **Reject.**
3. Though staining the sections will make it possible to observe the internal cell structures, there is still the same problem as in Procedure #2 because the 20 sections are taken from 20 different pieces of tissue. **Reject.**
4. **Best Answer.** Looking at 20 consecutive sections of a cell from the same piece of tissue will give a complete picture of the internal structure of a cell because those 20 sections make up one cell. Since those sections are stained, it is possible to observe the internal cell structures.
5. If neither #2 or #3 is the Best Answer then certainly this cannot be the Best Answer for the same reasons as #2 and #3 are not. **Reject.**

This is a more difficult exercise and here are examples of two student justifications that you may expect to receive:

Student 1

1. One section is not enough to give the overall picture of what the scientist needs.
2. Both #2 and #3 are good answers because the scientist will be looking at 20 sections from 20 different pieces of tissue. This will give a view of all the different types of tissue. Staining the sections would help see them more clearly.
3. Same as #2.
4. This would not be a good answer because all 20 pieces of tissue would look alike.
5. Same as #2 and #3.

This student's responses are incomplete and especially in the case of Choice 4 are illogical. Most likely Choices 2 and 3 were picked because of the student's belief that two choices mean you are twice as likely to select the correct answer.

Student 2

1. Looking at one section would give only 1/20 of the total picture, since there are 20 sections. **Reject.**
2. Looking at 20 sections from 20 different pieces of tissue would give a random picture. They should be from the same tissue. **Reject.**
3. The stained sections are the ones that should be viewed. Viewing the different, unstained sections does no good. **Reject.**
4. **Best choice.** Twenty consecutive stained sections of a cell from the same tissue would give an overall picture of that particular cell.
5. See #2 and #3. **Reject.**

This student gave a satisfactory argument for each choice. For example, in Choice 1 it was indicated that one section would give only 1/20 of the total picture and in Choice 2, 20 different pieces would only give a random view. Suggesting to the students that they draw a picture of the sectioned cell may give the students a better understanding of the problem.

These examples provide typical student responses. Many students have obvious difficulties in structuring a sound argument with concepts and information they should have learned. Their written justifications are an invaluable source of information to the teacher on student deficiencies in both information and critical thinking skills. When required and graded on a regular basis, the teacher should provide frequent feedback to students on their progress. Some students will at first write: 1. False, 2. False, 3. False, 4. True, 5. False as an answer to this exercise. This is not an acceptable response, and you must describe to the students what you expect as an acceptable answer to each exercise.

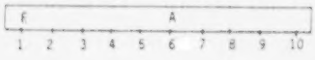
Writing useful exercises is a challenging and difficult process for instructors. These exercises are much more difficult to produce than the more typical recall problems. However, with some thought and practice and attention to the guidelines described earlier, you can begin to develop productive exercises.

Example Number 3

This example is particularly revealing of student misunderstandings. Even though the concepts and application are straight forward, students have an unusual amount of difficulty.

A biologist prepared a strip of agar (a gelatin-like substance) as shown in the figure below. At Position 6 he placed a concentrated sample of Amino Acid A and at Position 1 a concentrated sample of Enzyme E. E is known to catalyze the conversion of A to a Product P. Assume that A and E can diffuse through agar and that smaller molecules can diffuse much more rapidly than larger molecules. At what position would you most likely first find P?

1. 7 2. 6 3. 2 4. 4 5. 5



Analysis

E = larger molecule
A = smaller molecule

1. Position 7

Enzymes are proteins that are composed of many amino acids. Therefore, you would expect an enzyme to have a far higher molecular weight than an individual amino acid. Since both molecules are diffusing through the agar and larger molecules move more slowly than smaller molecules, you would not expect P to first form at Position 7. This meeting place is impossible, no matter what the relative rates of diffusion of E and A. If they both diffuse, their first meeting must be between E and A (Positions 1-6). **Reject.**

2. Position 6

Lighter molecules move faster than heavy molecules. Both molecules are diffusing through the agar (see question stem). You would not expect P to first form at 6 because this would require a larger molecule to diffuse faster than a smaller molecule and would indicate that A is not diffusing, which is contrary to the information in the stem. **Reject.**

3. Position 2

Best choice. See #2 above. A is a lighter molecule and would therefore diffuse faster and travel a greater distance per unit

time. A diffuses 4 units while the larger molecule (E) diffuses 1 unit before P forms. This is consistent with what we would expect, assuming that both A and E were placed on the agar at the same time.

4. Position 4

See #2 above. The product would not form first at 4 as this would require a larger molecule to move faster than a small molecule. **Reject.**

5. Position 5

See answer #4. The larger molecule (E) does not move faster than the smaller molecule (A) therefore P will not first form closer to Position 6. **Reject.**

This problem appears fairly simple and meets the criteria set forth for good practice problems. The knowledge expected from students should have been covered many times in class (enzymes are proteins that are composed of amino acids; therefore, enzymes are much larger than amino acids), new and appropriate information is supplied in the problem (large molecules diffuse slower than small ones), and the problem presents an unfamiliar and imaginative situation. On a standard multiple-choice exam only 22 percent of 204 students could answer this question correctly as shown by a recent analyses. Students have an exceptionally difficult time with this problem. Many answers are typical of the responses given by Student 1.

Student 1

1. The reaction would occur between A and E, so obviously the reaction would not occur at 7.
2. The diffusion would move left from A, so they would meet not on A but between A and E.
3. I think the reaction would be further away for E than at Position 2.
4. The best answer. E would be a little faster and 4 is also much more in the middle.
5. Too close to A. Needs to be a little more in the middle.

This student is arguing that the enzyme is smaller than an amino acid—information contrary to that provided several times in class.

Other students pick the best choice but demonstrate poor reasoning and are not given credit for the problem.

Student 2

1. **Reject.** It can't be seven because when they diffuse they won't go past six.
2. **Reject.** It can't go past six because they will diffuse in the middle of one and six.
3. **Best choice.** The catalyst is going to speed up the reaction so that it would get to two and stop.
4. **Reject.** A is moving faster because of the diffusion, but the enzyme is a catalyst and it speeds up.
5. **Reject.** The catalyst is going to speed up the reaction.

For this student, the catalytic action of the enzyme is important, but this approach provides no logical basis for solving the problem. Other students, such as Student 3, provide an excellent analysis.

Student 3

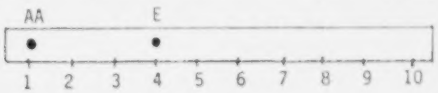
1. Answer 7 would not be possible because the enzymes and amino acids would meet before that point.
2. The amino acid would have diffused already so the point where they first meet cannot be Point 6.
3. This would be the best answer because enzymes are made up of amino acids and would therefore move slower than the amino acids.
4. The enzymes speed up the amino acid as they meet so the amino acid would be traveling faster than the enzyme and therefore could not meet at Point 4.
5. Not likely because the enzyme would be moving much faster (four times faster) than the amino acid and it is supposed to be a catalyst.

The quality and differences in these three responses should be obvious. Many teachers who try this problem with their students are surprised and even shocked at the responses. Even after repeated exposure to the necessary material in lecture, laboratory and text, students misapply information when faced with a new problem requiring unfamiliar applications and the structuring of a logical argument. Building skills and applying scientific concepts in an analytical way requires practice with a variety of problems, not the exposure to more information or repetitious exposure to the same information. This problem also illustrates how one question may lead an instructor to write a second question based on the previous

exercise. With practice, questions become easier to think of and write.

A New Problem

A student places an enzyme (E) and an amino acid (AA) on the agar strip plate shown below at the positions indicated. AA and E can diffuse through agar. When the enzyme and amino acid diffuse to each other and meet, the enzyme catalyzes the conversion of the AA to a yellow precipitate.



The student predicts that the yellow precipitate will first be observed at Position 3 on the strip. (Remember that large molecules diffuse more slowly than small molecules.) Which of the following is the student most likely assuming?

1. The enzyme will diffuse toward 6 as well as toward 3.
2. The yellow precipitate will form at Position 3.
3. If E were placed at 1 and AA at 6, the results would be different.
4. The enzyme and AA were placed on the agar at the same time.
5. The enzyme is placed on the agar strip at Position 4.

This problem is an example of an assumption problem as described in Chapters 2 and 3.

How are student responses evaluated? Once suitable exercises are available (see reference number 4 and 5 for additional examples of problems), the evaluation of student responses, both verbal and written, is essential to provide effective feedback and assess student progress. When evaluating our students, the following guidelines are extremely useful:

1. Insist on complete, unambiguous and well-argued justifications. Teachers often have a tendency to give students a break when they use the right words, thinking that the students probably know what they are talking about even though their answer is not clear. This is a mistake. If you expect good answers, you will get them; if not, you will encourage poor decision making, sloppy analysis and incomplete answers.
2. On written analyses of multiple-choice questions, give no credit for just picking the right choice. Being able to make a good argument is what counts, not simply "picking a winner." In some of these examples students selected the right choice but had poor arguments.
3. Expect students to exercise good judgment. Several choices may be possible but the question is, what is most likely? Students would much prefer to work with right or wrong answers, and so would many teachers because the reasoning required can be much easier. Indeed, many students are easily misled by choices that are true statements but have nothing to do with the problem.
4. Be prepared to discuss the rationales and justifications with students at some length. Admit and give credit for those parts of their arguments that are acceptable, but be ready to spend some time describing where they went wrong. Again, students expect right or wrong answers and extended discussion is often interpreted as "beating around the bush" or making excuses. It takes practice to change these behaviors.

In summary, one last example illustrates both the difficulties and progress for our students. Often in a lecture, we will discuss at length the multiple-choice problems. Students are asked to provide justifications for accepting or rejecting each choice. When finished, some student almost always says, "I know all that, but I couldn't make the argument come out the way you did." To which we reply, "Yes, but we have had 20 years more practice than you. With continued practice, you will get much better."

REFERENCES

Stroup, D. J. & Allen, R. D. (1992). *Critical thinking - A collection of readings.* Wm. C. Brown Publishers. 132 pp.

Statkiewicz, W. R. & Allen, R. D. (1983). Practice exercises to develop critical thinking skills. *Journal of College Student Teaching, 12,* 262-266.

Crow, Linda W. (Ed.). (1989). Chapter 3. *Enhancing critical thinking in the sciences.* Washington, DC: Society for College Science Teachers. 117 pp.

Taylor, J. B. & Jackson, J. D. (1992). *Study guide and workbook for Starr and Taggart's Biology, the unity and diversity of life.* (6th ed.). Belmont: CA: Wadsworth Publishing Company. 556 pp.

Instructor's manual to accompany Curtis and Barnes' Biology, Fifth Edition. (1990). New York: Worth Publishers, Inc.

Annotated Bibliography

These references are in addition to those cited in the text.

GENERAL REFERENCES

1. Critical Thinking Skills. M. Heiman and J. Slomianko. National Education Association. Washington DC. 1985. 48 p.
   A relatively short description of several practical classroom techniques to improve critical thinking skills. These include divergent thinking, writing, feedback and working in pairs.
2. Education and Learning To Think. Lauren B. Resnick. National Academy Press, Washington, DC. 1987. 62 p.
   Emphasizes research background and implications for teaching thinking skills in areas such as reading and study, informal logic, and self-motivation. A strong argument is made to embed thinking skills in academic disciplines.
3. Understanding Scientific Reasoning. Ronald N. Giere. Holt, Rinehart, and Winston, New York. 1979. 371 p.
   Scientific reasoning described in some detail using Newtonian mechanics and Mendelian genetics as major examples. Emphasizes formal logic as an approach to analyzing scientific experimentation.
4. Teaching Thinking Across the Curriculum. Vincent R. Ruggiero. Harper and Row, New York. 1988. 223 p.
   An extensive review and description of thinking skills, instructional materials, and instructional objectives in a variety of disciplines.
5. Critical Thinking: Theory, Research, Practice, and Possibilities. Joanne G. Kurfiss. Association for the Study of Higher Education. Washington, DC. 1988. 148 p.
   Discusses informal logic, cognitive processes, and developmental foundations of actual thinking. Includes excellent examples of thinking skills instruction in a variety of disciplines.
6. Inside intelligence. Robert J. Sternberg. "American Scientist". 1986, Vol. 74(2), 137-143.
   An excellent short article describing cognitive science and recent research results. This is probably the best introduction for those not familiar with cognitive science.
7. Critical Reasoning. Jerry Cederblom and David Paulsen. Wadsworth Publishing Co. Belmont, CA. 2nd Edition. 1982.
   A good general introduction based on formal logic. Many practical examples and illustrations are provided.
8. Problem Solving and Education. David Tuma and Frederick Reif, Eds. Lawrence Erlbaum Associates. Hilldale, NJ. 1980.
   Chapters contributed by a variety of researchers and teachers. Some chapters are highly theoretical, but the book does address many teaching problems and strategies.
9. Cognitive Process Instruction: Research on Teaching Thinking Skills. Jach Lochhead and John Clement, Eds. The Franklin Institute Press. Philadelphia, PA. 1979.
   Similar to previous reference but with more emphasis on teaching science and mathematics.

REFERENCES ON BIOLOGY TEACHING

1. The Nature of Scientific Thinking as Reflected by the Work of Biologists & by Biology Textbooks. Al Gibbs and Anton E. Lawson. "The American Biology Teacher." March 1992. Vol. 54(3), 137-152.
   Discusses many inconsistencies and inaccuracies on scientific thinking described in biology textbooks.
2. Teaching Thinking Skills in Biology. Barry K. Beyer and Ronald Charlton. " The American Biology Teacher." 1986. Vol. 48(4), 207-212.
   Teaching procedures described in this article are somewhat simplified but the introductory material is informative.
3. Developing Critical Thinking in Biology. M.B. Moll and R.D. Allen. "Journal of College Science Teaching." 1982. Vol. 12(2), 95-98.
   Describes procedures used in an introductory biology course. Data are presented which indicate improvement in critical thinking skills.

CRITICAL THINKING MEETINGS & NEWSLETTERS

1. Newsletter. Inquiry - Critical Thinking Across the Disciplines. The Institute for Critical Thinking. Montclair State College, Montclair, NJ.
2. Conference. Annual Conference on Critical Thinking and Educational Reform. Sonoma State University, Sonoma, CA.
3. Newsletter. Teaching Thinking and Problem Solving. Research for Better Schools. 444 North Third Street, Philadelphia, PA 19123.
4. Newsletter. Strategies for Success. Benjamin/ Cummings Publication for Life Science Instructors.
5. Critical Literacy Project. Oakton Community College. 1600 East Golf Road, Des Plaines, IL 60016.

About the Authors

Allen

Stroup

Robert D. Allen and David J. Stroup have worked together for over 15 years on instructional development and research, focusing their efforts on the development of students' critical thinking skills. As part of the National Science Foundation sponsored Chautauqua "Developing Critical Thinking in Science Teaching," they have presented over 40 national workshops on "Developing Critical Thinking in Science Teaching."

Dr. Allen received his PhD in biophysics from the University of California at Los Angeles, has held academic appointments at Purdue University and West Virginia University, and has served as president of the Society for College Science Teachers. He is currently serving as Vice President of Instructional Services at Victor Valley College, in Victorville, CA.

Dr. Stroup received his PhD in biological sciences from West Virginia University, Morgantown, WV. He has held an academic appointment at Clemson University and is currently a member of the Department of Biology at Francis Marion University.